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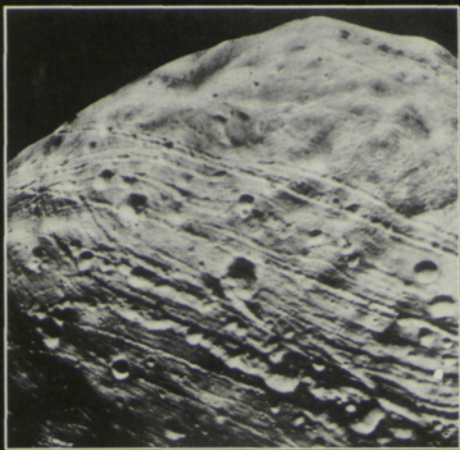

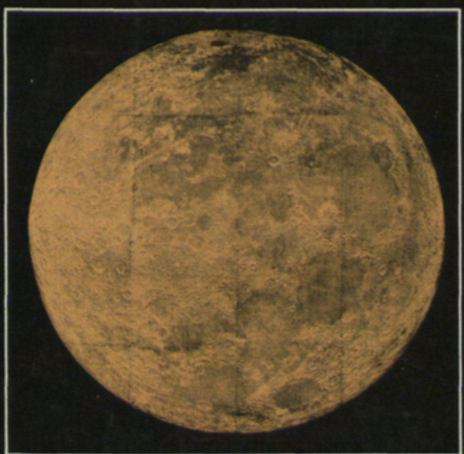

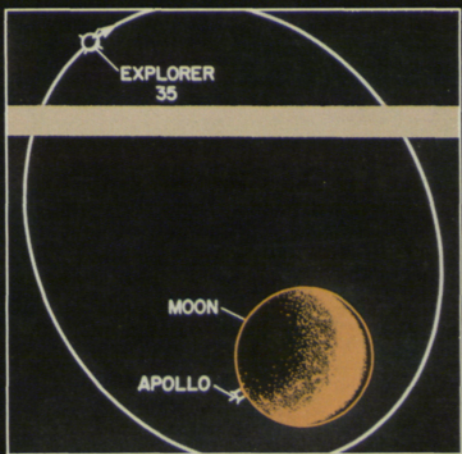

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PLANETS AND THEIR SATELLITES

IN THIS ISSUE

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Opposite: The Moon's surface, showing a mare in the foreground and highlands around the crater Kepler. Outside cover (clockwise): a detail of Phobos, a satellite of Mars; Saturn; a diagram showing the technique for lunar magnetometer measurements; Earth's Moon.

EXPLORING NEW WORLDS IN SPACE: THE OTHER MOONS

by Joseph A. Burns and Joseph Veverka

The investigation of worlds beyond our own is a relatively new venture in the long history of exploration. For several millenia explorers were confined to the surface of Earth. Only during the past two decades have we visited our Moon and sent spacecraft to some of the nearer planets. Now, at the present moment, two Voyager spacecraft are rapidly approaching Jupiter on a trip that will take both of them on to Saturn and perhaps one of them on to Uranus; and plans are being laid for the Galileo mission to Jupiter in the mid-1980's. A new phase in the exploration of our solar system is under way.

An intriguing aspect of the spacecraft missions is the opportunity to get a close look at the natural planetary satellites other than our Moon. Serious investigation of these satellites began in 1976, when the Viking Orbiters were programmed to make a series of very close approaches to Phobos and Deimos, the two moons of Mars. Now, with the Voyager missions, the exploration of the vast satellite systems surrounding the giant outer planets is about to begin. This is a good time to consider what we already know about the satellite systems of Mars, Jupiter, Saturn, and Uranus, what we expect to discover during the next decade, and what the significance of the information is likely to be.

WHAT WE MAY LEARN FROM STUDYING THE MOONS

Why are we so interested in the moons of the solar system? A major reason is that they mimic the Sun's family of planets in many ways and may yield information that will help us understand the origin and evolution of the planets. The inner satellites, like the planets, always move in regular orbits—that is, orbits which are nearly circular, roughly evenly spaced, and approximately in the equatorial plane of the central body. Usually these satellites revolve around their planet (in the same directional sense that the planet spins on its axis) in a manner that duplicates the direct revolution of the planets around the Sun. Such similarities suggest that the satellite systems may be viewed as solar systems in miniature and that their formation may have been closely analogous to that of the coterie of planets.

Fortunately, the origin of the moons may be easier to decipher than that of the generally much larger planets. Their smaller size implies less internal heating and consequent modification of the surfaces by internal activity. Also, most lack atmospheres and therefore have not undergone complicated weathering processes. It should be much easier to infer the early histories of these satellites from what we see on their surfaces today than it is to deduce the formation and evolution of the larger and very much more complicated planets.

Another advantage in studying satellites is that they come in great variety, providing ideal means for testing theories and models of surfaces, interiors, and origins. Some have surface areas not much bigger than the city of Ithaca, New York, and a few are comparable in size to the smallest planet. Some are made of rock, others predominantly of ice. Some are bright and shiny, others dull and black. A few have atmospheres, though most do not.

Actually, several of the natural satellites seem more like planets than some of the planets. Figure 1 shows that

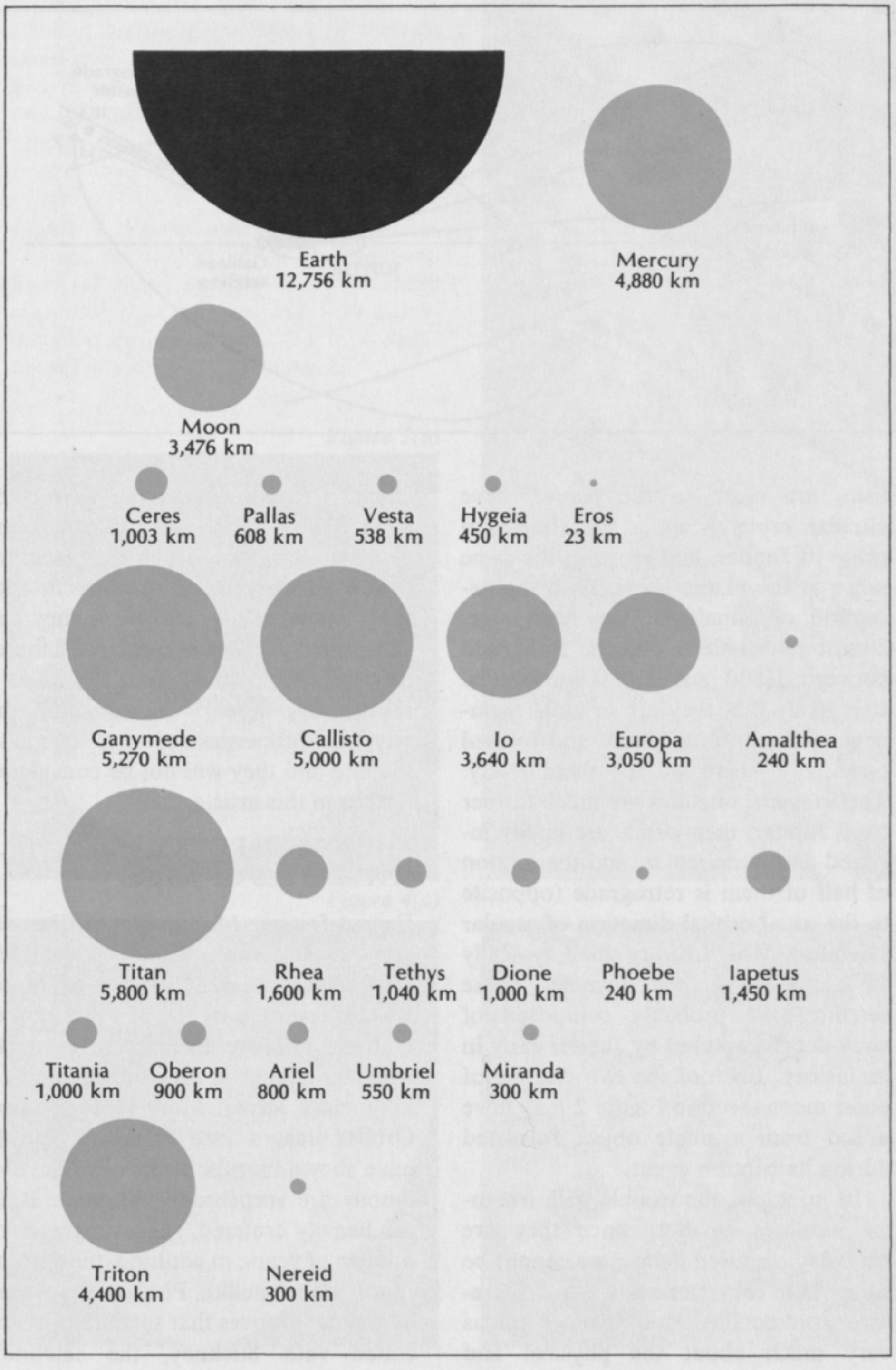


Figure 1. The diameters of selected satellites as compared with those of Earth and Mercury. A few asteroids (shown just below Earth's Moon) are also included. Three satellites are bigger than the planet Mercury and ten are larger than Ceres, the biggest asteroid. Not shown are sixteen other satellites: two of Mars, eight more of Jupiter, five of Saturn, and the most recently discovered one of Pluto. If drawn to this scale, most of these would be mere specks.

several of the moons are larger than Mercury. Titan, Saturn's largest satellite, has an atmosphere that is denser than those of Mars and Mercury. Even as seen by restricted ground-based instruments, Jupiter's Io exhibits phenomena that are as perplexing as those of any planet: excited gas clouds of sodium, potassium, and hydrogen that form toroids about its orbit, frost that only sometimes appears after the satellite is eclipsed by its planet, and a controlling influence over the amount of radiation emitted by Jupiter that is received by Earth. The puzzles presented by these and other phenomena already encountered in satellite studies may be

Figure 2

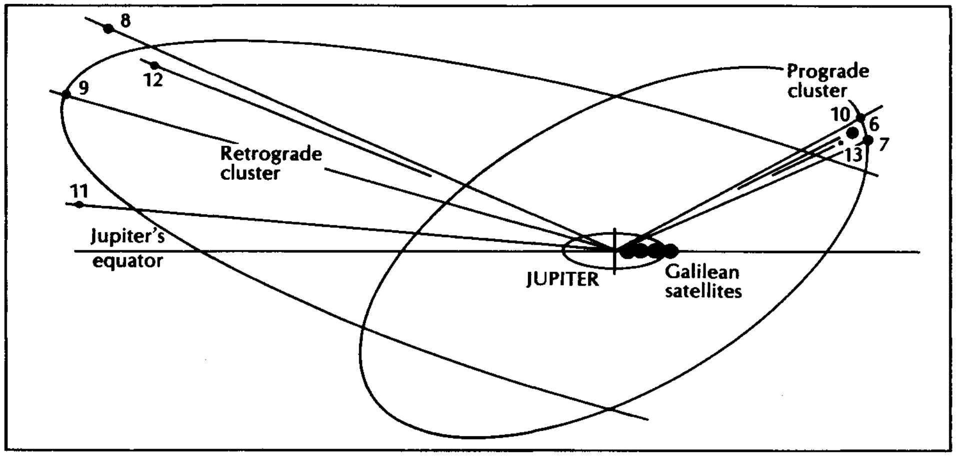


Figure 2. Orbital distances and inclinations for the Jovian satellite system. The regular *satellites lie in the planet's equatorial plane on circular orbits. The* irregular *satellites come in two clusters, one prograde and one retrograde; each is composed of members having similar orbital inclinations and ellipticities. Because of solar perturbations, there is at any specific time a variety of orientations of the orbital planes of members of a given cluster, so that the actual orbital planes are not aligned in three-dimensional space. The outer satellites range in size from a few to a hundred kilometers in radius; their relative sizes are crudely indicated by the sizes of the dots. The Galilean (regular) satellites are 1,500 to 2,650 kilometers in radius. The innermost satellite, Amalthea, only 120 kilometers in radius, is not shown in the sketch.*

solved when scientists get their first close-up look at the major moons. Undoubtedly, however, many other questions will arise, since our current knowledge of moons is so scant.

TWO MAIN CLASSES OF PLANETARY SATELLITES

In considering the moons of our solar system, we need first to distinguish between two distinct classes of satellites: regular and irregular.

Consider, for example, the Jovian system of thirteen known satellites (see Figure 2). The *regular* satellites, Amalthea, Io, Europa, Ganymede, and Callisto, are close to the planet, have circular orbits lying in the equatorial plane of Jupiter, and move in the same sense as the planet spins. With the exception of Amalthea, they are large, almost planet-sized objects, with radii between 1,500 and 2,650 kilometers. It is likely that they are original members of the Jupiter family and formed essentially where we see them today. The *irregular* satellites are much farther from Jupiter, their orbits are highly inclined and noncircular, and the motion of half of them is retrograde (opposite to the usual orbital direction of regular satellites). Most are very small, typically 10 kilometers or so in diameter. These satellites are probably composed of stray debris captured by Jupiter early in its history. Each of the two clusters of outer moons seen in Figure 2 may have arisen from a single object fractured during its capture event.

In principle, the trouble with irregular satellites is that, since they are probably captured debris, we cannot be sure where they came from, and therefore their detailed study cannot tell us very much about the physical and chemical conditions in the vicinity of what is now their parent planet at the time the planet and its regular satellites formed. In practice, the problem with these satellites is that, since they are very small, they are also faint and therefore difficult to study from Earth. As a result, very little is known about the physical properties of any irregular satellite and they will not be considered further in this article.

THE SMALL ROCKY SATELLITES OF MARS

Except for our Moon, the satellites we know most about are Phobos and Deimos, the two small moons of Mars. Images returned by the Mariner spacecraft in 1971 revealed them as dark, irregular chunks of rock only 27 and 14 kilometers across. More recent Viking Orbiter images (see Figures 3 and 4) have shown that the surfaces of the two moons are surprisingly different. Both are heavily cratered, suggesting ages of billions of years; in addition, the surface of the inner satellite, Phobos, is covered by unique grooves that seem to be associated with Stickney, the satellite's

Figure 3. Viking spacecraft views of Phobos, the inner and larger of the two small satellites of Mars. Phobos is 27 kilometers long. (a) shows the satellite's largest crater, Stickney, and some of the surface grooves that appear to be associated with it. (b) shows surface detail.

Figure 4. Viking spacecraft images of Deimos, the smaller of the Martian satellites. (a) shows Deimos to be generally smoother than Phobos, but with patchiness in surface albedo. (b) is a detail taken from about 100 kilometers.

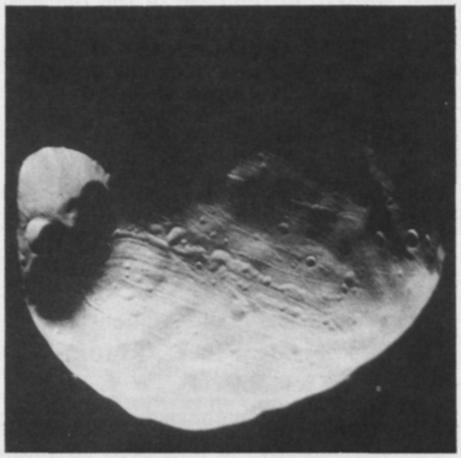
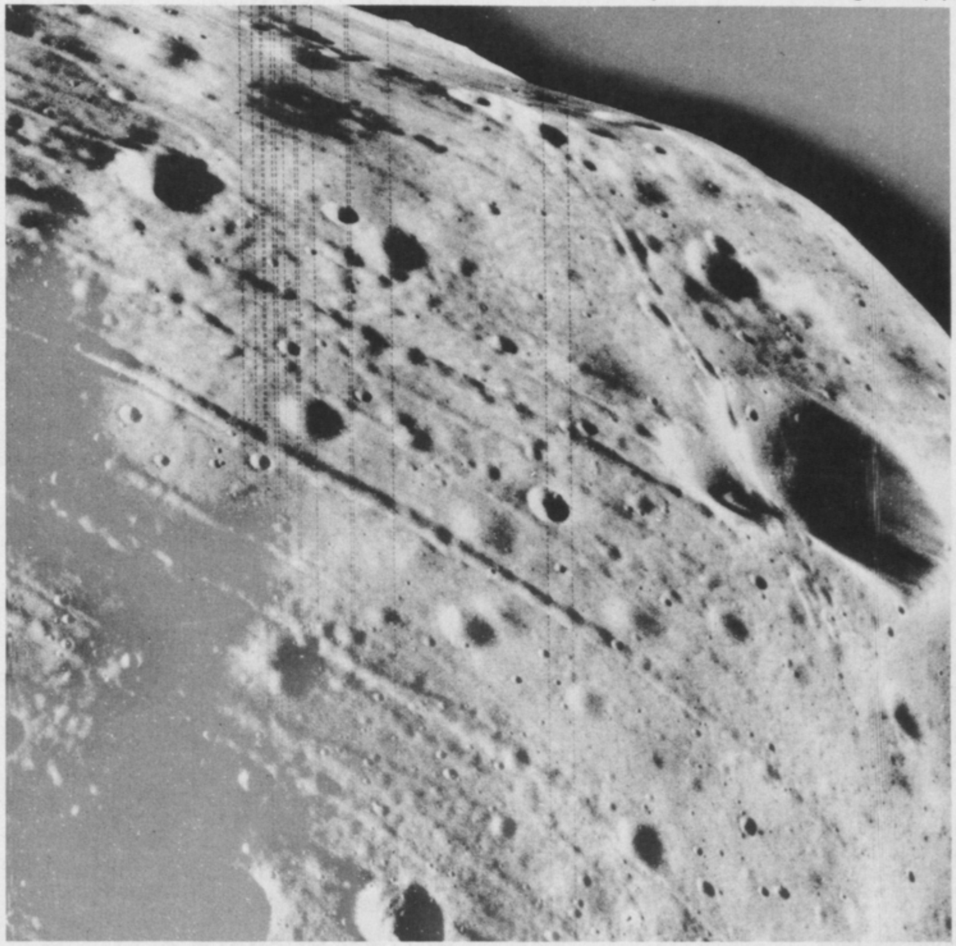


Figure 3(a)



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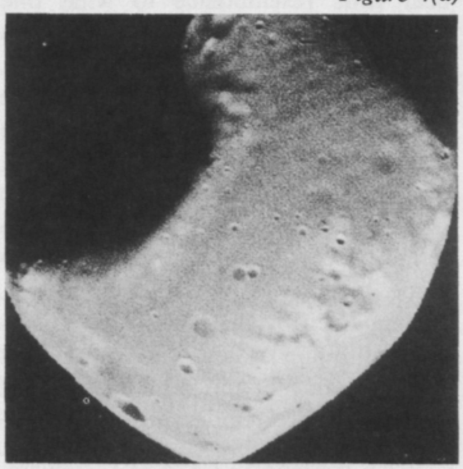


Figure 4(a)

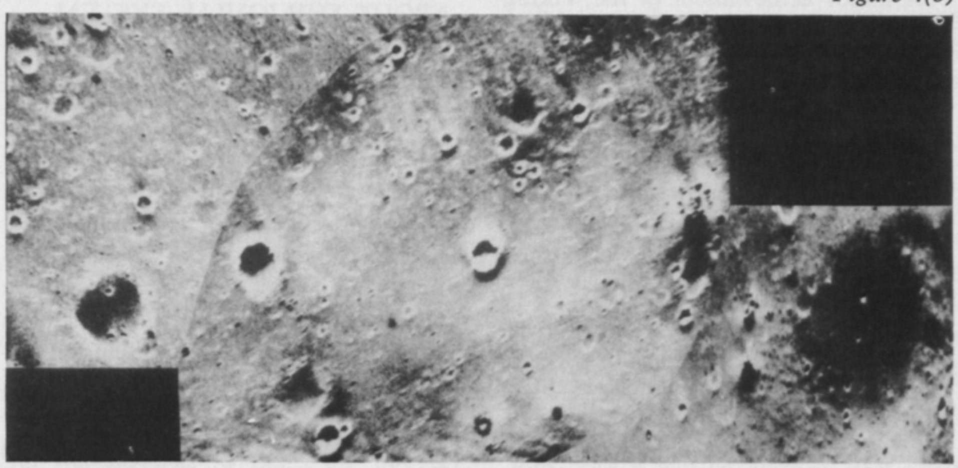


Figure 4(b)

largest crater. (One hypothesis is that the grooves represent cracks caused by the very severe impact that produced this large 10-kilometer crater on the tiny satellite; see the article in this issue by Peter Thomas and Arthur L. Bloom). Furthermore, many of the craters on Deimos appear to be partially filled with brighter debris quite unlike anything visible on Phobos. Why the surfaces of these two satellites, so similar in size and both located close to Mars, should be so different is still a matter for speculation.

A major achievement of the Viking mission was to maneuver the spacecraft close enough to the satellites to feel their gravitational pull; this permitted the calculation of their masses and mean densities. Viking Orbiter 1 flew within 100 kilometers of Phobos, and Viking Orbiter 2 came within 23 kilometers of Deimos. Both satellites turned out to have low densities (less than 2 grams per cubic centimeter) similar to those of some meteorites (the carbonaceous chondrites), which also seem to match the satellite surfaces in their dark color. If confirmed, the characterization of Phobos and Deimos as low-density carbonaceous chondritic matter will be significant, for this material is believed to have formed only in the outer reaches of the asteroid belt. Thus, Phobos and Deimos could be captured objects, although it is not easy to develop a scenario that produces orbits as regular as those the two satellites have today.

Incidentally, Phobos will not be with us much longer. Martian tides are drawing energy out of its orbit at a rapidly increasing rate, making the satellite spiral in toward the planet. It has been calculated that in another 50 million years—astronomically an insignificant amount of time—Phobos will be gone.

Studies of the Martian satellites provide an important test of our understanding of the processes that operate on the surfaces of very small bodies with almost no gravity—bodies such as the many asteroids that populate the space between Mars and Jupiter. Since we are unable to explain conclusively the striking differences in the surfaces of Phobos and Deimos, it would appear that our current understanding is in need of considerable refinement.

WHAT IS KNOWN ABOUT THE JOVIAN SYSTEM

The four large inner satellites of Jupiter—often called the Galilean satellites after their discoverer—mimic the planetary system in two important ways. One is the regularity of their orbits, already mentioned. The other is a decrease in the mean density of the satellites with increasing distance from Jupiter, much like the density decrease that occurs in the solar system, differentiating the terrestrial inner planets from the giant gaseous outer planets. The inner two Jovian satellites, Io and Europa, have densities like those of common rock, while the outer moons, Ganymede and Callisto, are considerably less dense and must contain significant amounts of water and ice. Current models suggest that Ganymede and Callisto consist of rocky cores surrounded by mantles of watery slush, topped by crusts of water ice.

The gradations in density and composition that we see in the Jovian satellites and in the planets are believed to have been produced in analogous ways. Each system formed out of gas and dust clouds surrounding an intense central heat source; in the case of the planets, this was the Sun, and in the case of the Galilean satellites, it was the red-hot proto-Jupiter. In both systems, the results were the same. Close to the heat source, temperatures were very high and only rocky materials, which have very high melting temperatures, could condense as solids. Farther out, temperatures were cooler and the much more volatile ices could condense, along with less abundant rocks, to form predominantly icy objects.

One remarkable characteristic of the Galilean satellites is that their surfaces bear little resemblance to what one might expect from a naive extrapolation of models of the interiors. For example, the rocky satellite Europa has a surface of water ice, while the icy satellite Callisto has a dark, and probably rocky, exterior. These differences are evidence of modification by both internal and external processes. Internal processes include melting of the interior matter, accompanied by the release to the surface of liquid water, and subsequent rapid freezing of the water because of the low surface temperature of the satellites. External processes include coat-

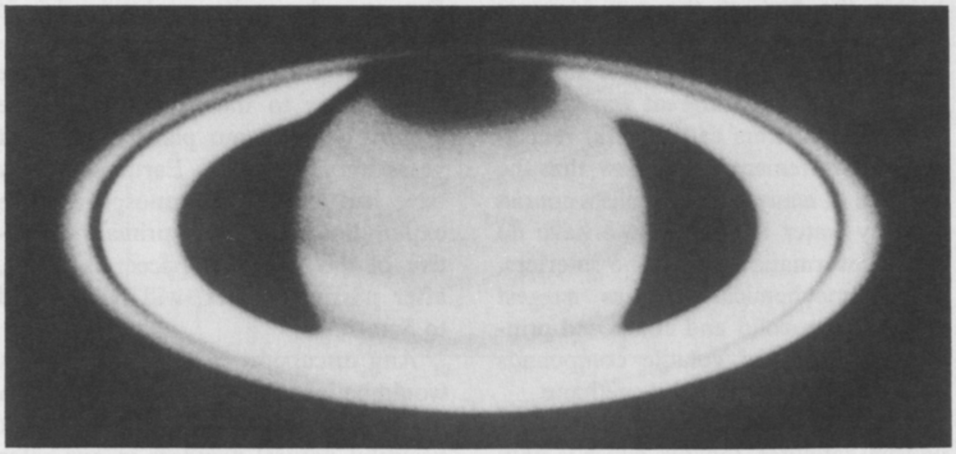


Figure 5. A telescopic photograph of Saturn and its ring system. Features readily discernible are the outer A ring and the brighter B ring, both partially transparent and separated by the Cassini division. Two faint inner rings, C and D, and a very faint exterior one are also believed to exist.

ing of the surfaces with micrometeoroid debris falling into the Jupiter system, and alterations of the mineralogical and chemical composition of the surface caused by exposure to high-energy charged particles in Jupiter's van Allen belts.

Consider, for example, the innermost Galilean satellite, Io, which is in the thick of the radiation belts. It has a bright yellow surface entirely devoid of frost. Theoretical models suggest that Io is large enough and contains enough radioactive material so that its inside could have heated up and melted about 3.5 billion years ago. Presumably water saturated with easily dissolved salts was produced as a result of this melting, and was forced out onto the surface, where it promptly froze. But Io did not retain its coating of ice very long. The bombardment of the surface by high-energy protons from Jupiter's van Allen belts is so intense and protons are so efficient at sputtering water ice, that the surface was soon stripped of all ice and only the salts, rich in sodium, potassium, and sulfur, among other elements, remained. The effect of charged particles on Io's surface did not stop there, however. The particles also converted some of the sulfate in the salts into elemental sulfur, giving Io its unique yellowish color. Even to this day, the bombarding particles continue to knock off individual atoms, which Io leaves behind as it moves in its orbit. Some of these atoms, such as those of sodium and potassium, glow in the sunlight, so that Io is followed, in its motion around Jupiter, by a spectacular doughnut-shaped, trailing cloud of luminescent atoms.

The next Galilean satellite, Europa, seems to be far enough from the radiation belt to retain a coating of water ice: the flux of high-energy particles has not yet been sufficient to entirely strip the surface of water ice. The outer two satellites, Ganymede and Callisto, presumably have very thick icy crusts because they are distant enough from Jupiter to make the amount of sputtering minimal. Planetary scientists are anxiously awaiting the return next year from the Voyager spacecraft of the first pictures of these bodies. What kinds of unusual geological features will be seen on the surfaces of these icy moons? Since the two satellites are expected to have mantles of liquid water topped by crusts of ice, some geologists have predicted large patterns of surface cracks, perhaps similar to the tectonic patterns on Earth's crust. Others have predicted volcanoes that are made not of rock, but of ice, and that spout hot water instead of molten rock.

A close study of the surfaces of Ganymede and Callisto will be one of the prime objectives of the Galileo mission in the mid-1980's. In this exploration, a sophisticated spacecraft will orbit through the Jovian system, using the gravity fields of the satellites to bounce from one close approach to another.

A VOYAGE TO SATURN AND ITS SATELLITES

Saturn's system of satellites is almost as grand as that of Jupiter: it contains fewer large moons, but has the distinction of including the largest satellite in the solar system, giant Titan. Because of Saturn's great distance from Earth, we know relatively little about its satellites, and it will be another four years

"...the exploration of the vast satellite systems surrounding the giant outer planets is about to begin."

before the first of the two Voyager spacecraft arrives there. But from observations of how the satellite surfaces reflect sunlight of different wavelengths (what astronomers call spectral reflectance measurements) we know that the surfaces of many of the satellites consist of dirty water ice. So far we have no direct information about the interiors, but cosmochemical theories suggest that they are solid and composed principally of ices of volatile compounds like water, ammonia, and methane.

The Saturn system has at least three unusual satellites. Iapetus, which is sixty Saturn radii from the planet, has one hemisphere darker than lampblack and the other covered with bright water frost. Renegade Phoebe, the small outer satellite, moves around the planet in a retrograde sense (backwards relative to the motion of the other satellites and the spin of the planet); it is probably a captured object rather than one of Saturn's original satellites. And then there is giant Titan, the largest moon in the solar system (almost twice the size of our Moon) and the only one big enough to have retained a substantial atmosphere.

Spectroscopic observations of Titan from Earth show that the atmosphere could be as dense as that of Earth and is made up of methane with, possibly, some hydrogen or nitrogen. Surprisingly, these and related observations prove that Titan's atmosphere is very cloudy, the topmost clouds being smoglike particles of complex organic compounds that give the satellite its characteristic reddish orange color. This telltale color, also seen in the belts of Jupiter and Saturn, is characteristic of organic compounds produced by the action of ultraviolet photons from the Sun on reducing atmospheres, rich in methane and hydrogen. The photochemical processes involved may be very similar to those that led to the origin of life on our planet billions of years ago, when the Earth also may have had a reducing atmosphere. The exploration of Titan is a primary objecttive of the Voyager spacecraft which, after passing Jupiter, will be targeted to Saturn.

Any discussion of Saturn's satellites would be incomplete without a mention of the planet's rings, one of the most beautiful natural wonders in our solar system. For almost a century, astronomers have realized that those rings consist of innumerable particles, each circling the planet on its individual orbit. Very recently astronomical and radar observations have shown the particles to be snowballs—objects a few centimeters in diameter, made of dirty ice.

Astronomers have been increasingly successful in understanding the structure of the rings: why they appear to have relatively sharp edges and why they are separated from each other by gaps such as the easily visible Cassini division. The culprits seem to be large and close satellites, which exert a periodic gravitational pull on any particle that strays outside the ring boundaries. As a consequence, the only stable orbits in this region reside within the confines of the ring system.

The rings lie within Saturn's Roche limit, the distance within which the planet's tidal forces overwhelm the mutual gravitational attraction of any two small particles. This means that particles within this distance cannot cluster and coalesce into a larger satellite. One view of the origin of the rings is

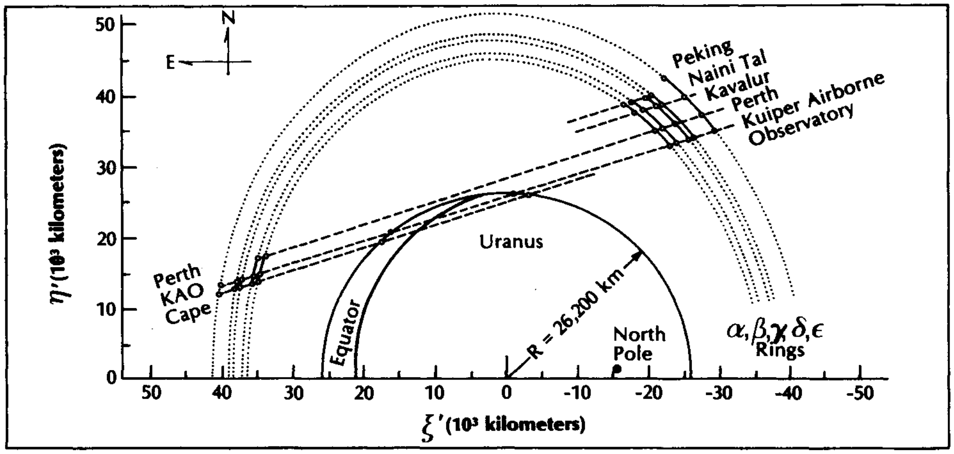


Figure 6. The relative position of the rings of Uranus as discovered unexpectedly in 1977 during a stellar occultation. The star's light was obscured on passage behind the rings and the planet. The best data were obtained by a group of Cornell researchers on the airborne Kuiper Observatory. Illustrated are the tracks of the star as seen from different observatories on Earth. Less extensive rings have been found during subsequent stellar occultations.

that they represent material left over from the formation of the Saturn system, material that never could form into larger bodies because, lying within the Roche limit, it is continuously disrupted by tides. Another opinion is that the material represents the debris of some unfortunate satellite or comet that happened to stray too close to Saturn and was torn apart by the planet's tides.

Direct exploration of the environs of Saturn by spacecraft will tell us much more about the rings. The Pioneer 11 probe will skirt the rings in the fall of 1979 to provide a little further information, and much more will be obtained from the flybys of the two Voyagers in 1980 and 1981.

THE ORDERLY MOON SYSTEM OF A TILTED PLANET

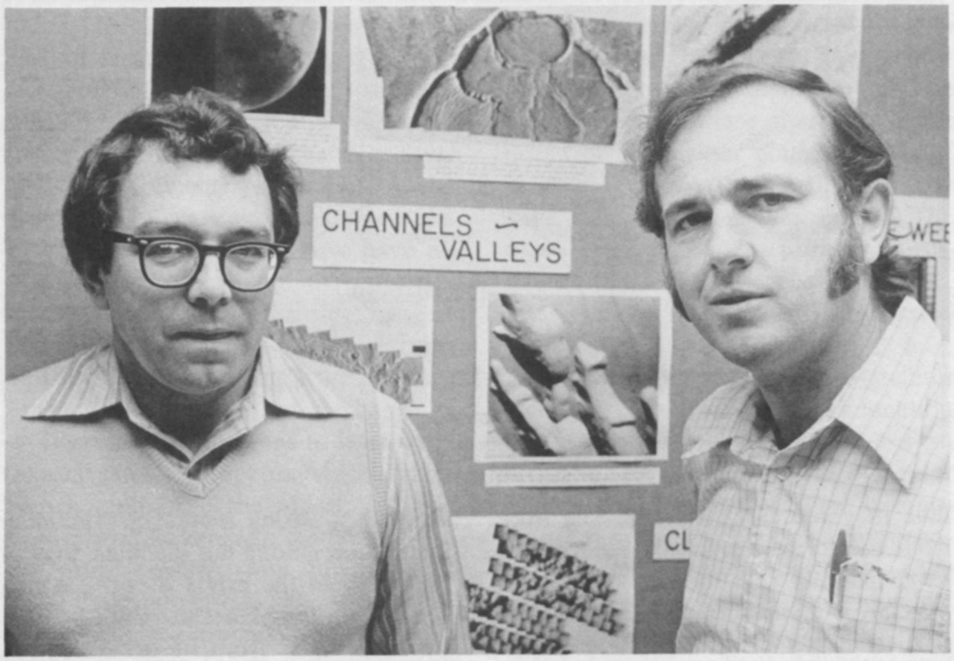
Dynamically, the satellites of Uranus form the most orderly of all the satellite systems. Four of the five moons have virtually circular orbits lying precisely in the equatorial plane of the planet. Their periods, relative to one another, are almost equal to the ratios of simple numbers (⅔, ½, etc.), which suggests a strong mutual gravitational interaction among the satellites. Such a regularity in the orbits is perhaps surprising, for the planet's equator is tilted by almost 90° from its orbital plane. Since it is unlikely that Uranus started out in this lopsided orientation, one wonders why whatever tilted the planet apparently did not disturb the satellites.

A major astronomical discovery of this century was the finding in 1977 of a series of at least nine rings surrounding Uranus (see Figure 6). These were identified during an occultation of a star by the planet; the best data came from aircraft observations by a Cornell team consisting of James Elliot, Edward Dunham, and Douglas Mink. In contrast to the rings of Saturn, the rings of Uranus are very narrow (eight of the nine are less than 10 kilometers wide) and separated by wide gaps; the particles are dark and almost certainly not made of water ice. All the rings lie in the planet's equatorial plane; however, some are not circular and they have variable widths. These rings, too, contain as yet undeciphered clues as to how satellites are formed.

EXPLORATION AND DISCOVERY IN OUR SOLAR SYSTEM

It is apparent that the thirty-three known natural satellites of planets in our solar system are disparate objects, vauable for the variety of information they can provide. Knowledge about them has increased greatly during the 1970's and will continue to grow during the next decade as a result of the Voyager and Galileo missions. We may soon discover much about these curious objects—their appearance, size, atmospheres, and composition, their history, and their place in the solar system hierarchy. Such an understanding will provide critical clues to the mystery of how our solar system originated and evolved.

The investigation of the moons of our solar system is, indeed, an important scientific undertaking. But to those who anticipate the first close-up views of the satellites of Jupiter, Saturn, and maybe even Uranus, it is also an exciting adventure. These scientists are today's explorers, successors to those who sailed the seas, crossed continents, set foot on the Moon, and sent the first spacecraft to neighboring planets.



Cornell's Joseph Veverka (at left) and Joseph A. Burns are specialists in planetary studies.

Joseph A. Burns, associate professor of theoretical and applied mechanics, joined the Cornell faculty in 1966 after completing his doctoral studies here in space mechanics, applied mathematics, and physics. His B.S. degree is from the Webb Institute of Naval Architecture, where he was awarded the Lewis Nixon Prize upon graduation.

His current research concerns the small bodies of the solar system (satellites, asteroids, and interplanetary debris), orbital evolution and tides, and the rotational dynamics and strength of pulsars, planets, and asteroids. Earlier work included research on turbulence stimulation, charged particle dynamics, kinetic art, and heuristic studies in classical mechanics.

Burns served as a National Academy of Sciences postdoctoral fellow in the theoretical studies division of NASA's Goddard Space Flight Center in 1967–68. For seven months in 1973 he traveled, lectured, and conducted research in the Soviet Union and Czechoslovakia as a National Research Council exchange fellow. During 1975–76 he was a senior investigator in the Theoretical and Planetary Studies Branch at NASA's Ames Research Center. He currently holds several NASA grants, including one for his work as guest investigator for the Viking mission.

He is a member of the American Association for the Advancement of Science, the American Astronomical Society, the American Geophysical Union, the International Astronomical Union, and Sigma Xi. He is editor of the recently published Planetary Satellites *(University of Arizona Press, Tucson).*

Joseph Veverka, associate professor of astronomy, came to Cornell in 1970 as a research associate in the Laboratory for Planetary Studies of the Center for Radiophysics and Space Research. He became a member of the faculty in 1974.

He has specialized in studies of the planets and their satellites, and has participated in many national space efforts. He worked on the flight team for the Mariner 9 TV Experiments (1971), the Viking Orbiter Imagery Team (1976–78), and the Special Team to Study Phobos and Deimos during Close Encounters in the Viking Extended Mission (1976–78); and at the present time he is a member of the Galileo Orbiter Imaging Team and the Voyager Imaging Team. He has also been active as a member of advisory groups and workshops for space programs. These have included the Titan Atmosphere Workshop, the Comet Halley Science Working Group, and the Asteroid Science Workshop. He is currently chairman of the NASA Comet Science Working Group.

In addition he has been active in professional organizations, especially as a member of committees on planetary and lunar science and exploration. He is a member of the American Astronomical Society and its Division of Planetary Sciences, the International Astronomical Union, the Royal Astronomical Society of Canada, the American Geophysical Union, and the Meteoritical Society.

He holds the B.Sc. and the M.Sc. degrees from Queen's University, Kingston, Canada, and the M.A. and Ph.D. degrees from Harvard University.

PHOBOS: A CAPTURED, FRACTURED ASTEROID?

by Peter Thomas and Arthur L. Bloom

Until spacecraft reached the vicinity of Mars, little was known about the planet's two natural satellites, Phobos and Deimos. They were discovered more than a century ago, but only within the last decade have we been able to find out what they look like. The best pictures, taken from 1976 to 1978 by the Viking Orbiters along with pictures of Mars itself, are remarkable in their detail and revealed a major surprise: Phobos, the larger of the two tiny satellites, is crossed by many parallel markings, variously described as striations, scratches, crater chains, or grooves, that presented a geological puzzle. No similar features have been found on any other object in space.

Here at Cornell we have studied the satellite pictures and formed a theory about the origin and structure of Phobos. We believe it may be a captured, fractured asteroid, intriguing in itself and suggestive of exciting possibilities in the exploration of asteroids.

DISCOVERY AND EXPLORATION OF THE MARTIAN MOONS

The story of the exploration of Phobos and Deimos began in 1877 with their discovery by Asaph Hall of the United States Naval Observatory. For many years, all that could be determined about them were their orbits and approximate sizes. Phobos was found to orbit Mars every 7.6 hours at a distance of about 6,000 kilometers. Deimos, with an orbital radius of about 20,000 kilometers, was found to require about 30 hours to go around the planet. The early calculations gave Phobos a diameter of about 15 kilometers (this was later proved too small) and Deimos a size about half of that.

In 1969 two Mariner spacecraft flew close to Mars and relayed television pictures that "accidentally" included Phobos. It was clear even from these

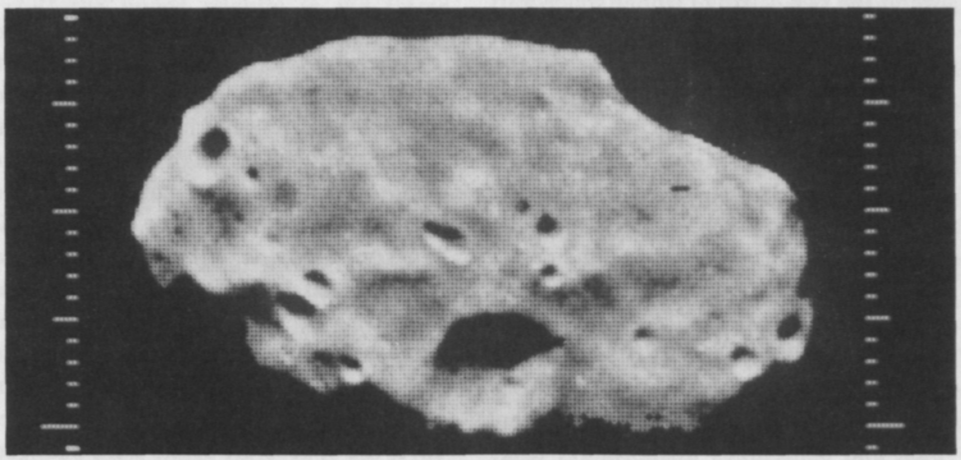


Figure 1. Phobos, imaged from 5,700 kilometers by Mariner 9 in 1971. The pictures obtained in this mission showed the irregular shape and some of the surface features of this natural satellite of Mars. Much more detail can be seen in the later Viking Orbiter images of the Martian moons (see Figures 2 and 5).

low-resolution images that Phobos is irregular in shape and almost twice as large as the early estimates (about 27 kilometers across in the largest dimension). The error in the size estimate was caused by assuming that Phobos reflects more light than it really does: it reflects only about 5 percent of the incident visible light, less than most common objects described as black.

Details of the surface of Phobos were first recorded by the television cameras on Mariner 9, which was placed in orbit about Mars late in 1971. Because Mariner arrived at Mars during an immense, planet-wide dust storm that obscured features on the planet's surface, the Martian satellites were imaged more than had been originally planned. Figure 1 is a typical Mariner 9 image of Phobos. It shows a very irregularly shaped object, much scarred by meteorite impact craters. Deimos was also shown to be irregularly shaped and heavily cratered. By comparing images taken many days apart, it was confirmed that both satellites always keep their long axes pointed toward Mars.

Impressive as the Mariner 9 images were, the two Viking Orbiter spacecraft that reached Mars in 1976 provided an almost bewildering increase in the details visible on the planet and its satellites. Better cameras and more opportunities to take pictures of the satellites produced hundreds of images of Phobos and Deimos on scales that have allowed nearly complete mapping.

Figure 2(a)

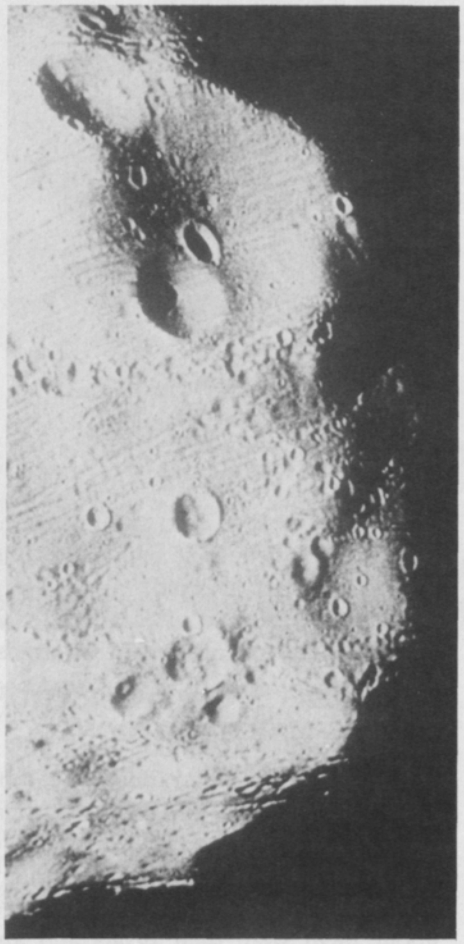


Figure 2. Grooves on Phobos, imaged from the Viking Orbiters in 1976. These unusual markings occur in parallel sets; they intersect some craters, but are interrupted by other younger craters. They appear to radiate from the large crater Stickney and may have been produced by the same impact.

In (a) the north pole of Phobos is at the top left and the distance covered is about 18 kilometers from top to bottom.

In (b) the rim of the large crater Stickney is at the left. The grooves here are up to 700 meters in width and 90 meters in depth. Several sets of grooves with different orientations are visible. The view is about 15 kilometers across.

(c) shows grooves emerging from the crater Stickney. The field is about 25 kilometers across and the view is from above the south pole.

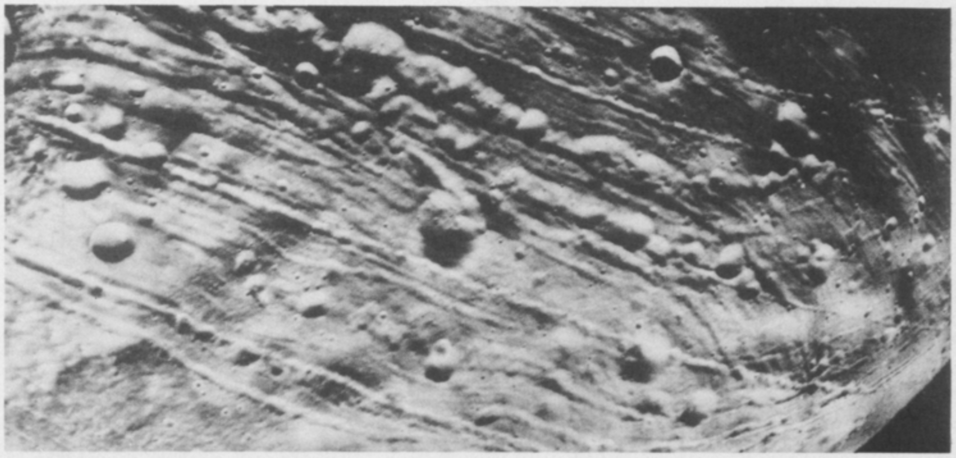
(d) shows two prominent sets of grooves in a field about 10 kilometers across. The grooves cross a very degraded crater in the center of the picture.

(e) is a close-up of the crater Hall, which is 5 kilometers in diameter. Several grooves are visible.

OBSERVING THE SATELLITES FROM THE SPACECRAFT

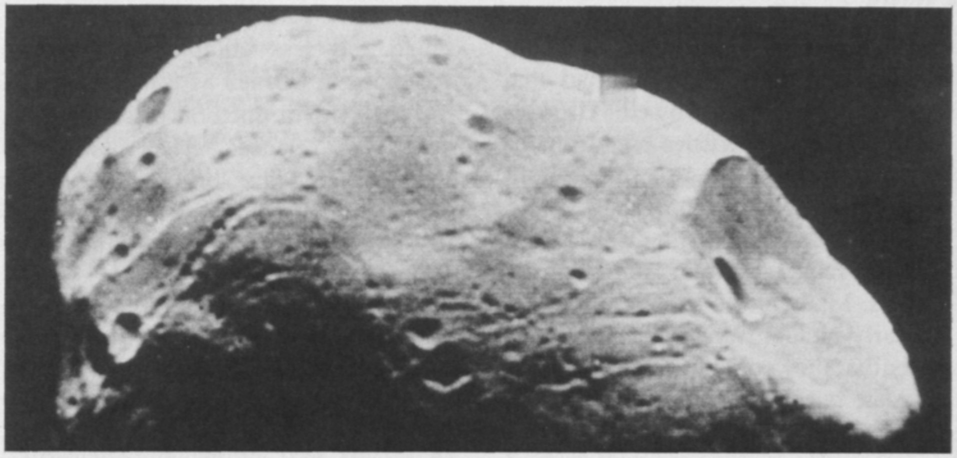
Imaging the two small satellites from the Viking spacecraft was a very complex and sometimes unsuccessful task. Both Phobos and Deimos move in nearly circular orbits that lie very close to the equatorial plane of Mars, and the spacecraft are in very elliptical orbits inclined at high angles to the equatorial plane (the inclinations of the orbits were dictated by the desired landing spots for the Viking Landers and by the need to image a wide range of latitudes on Mars). This meant that only rarely do the spacecraft come close enough to the satellites to take useful images. On several occasions, therefore, the spacecraft orbits were changed slightly to allow much closer approaches than would otherwise have occurred. This complicated procedure relied on extreme accuracy in the forecasting of spacecraft and satellite orbits, in the receipt of commands, in the pointing of the spacecraft, and in the firing of the onboard rockets to change the orbit. The close approaches were considered worth the effort, however, not only because they would permit very detailed imaging, but also because the mass of each natural satellite could be determined by tracking the spacecraft's de-

Figure 2(b)



(d)

(c)



(e)

flection from its established orbit as it passed under the influence of the planetoid's gravity.

The very close approaches entailed difficult circumstances for taking pictures. In order to include the satellites in the camera's field of view, which is only slightly over 1°, the spacecraft had to be given very accurate instructions for aligning the cameras and timing the exposures. The effect of tracking errors is greatest for the closest approaches: a position error of 10 kilometers at a range of 2,000 kilometers would simply shift the image slightly in the frame, but a similar error from a distance of 100 kilometers or less could cause an object to be missed entirely. The usual procedure for a close approach was to plan a series of images so as to allow for pointing errors; as it turned out, many pictures were, indeed, entirely blank. An additional problem was that since the spacecraft and the satellites were moving with high relative velocities, sharp images could be obtained only by compensating for the motion of the satellites in the field of view. The cameras had to be slewed as the images were being recorded.

At closest approach, the spacecraft came to within 97 kilometers of Phobos and 23 kilometers of Deimos. The closer approach to Deimos was dictated by the necessity to have the spacecraft come near enough to undergo a detectable perturbation of its orbit, for Deimos, being smaller than Phobos, has much less gravity.

In the close flyby of Phobos, one of the important findings was that the gravitational deflection of the Viking's

"No similar features have been found on any other object in space."

orbit was much less than had been expected. (The data on Deimos have not been completely processed.) Phobos apparently has a density of only about 1.9 grams per cubic centimeter, much less than that of the terrestrial planets. It is similar to the density of certain meteorites called carbonaceous chondrites, which may come from the outer part of the asteroid belt between Mars and Jupiter. It seems quite possible that early in the history of the solar system, one or more asteroids from this region were captured by Mars.

INTERPRETING THE VIKING PICTURES OF PHOBOS

As the pictures of Phobos began to be received from the Viking Orbiters, the unusual parallel markings on the surface became apparent (see Figure 2), and efforts were made to explain them.

One initial suggestion was that the striations or grooves had resulted from the exposure of sedimentary layers. Another idea was that they were caused by abrasion during a low-velocity collision with another body. As images covering more parts of the satellite were received, however, it became clear that the grooves occurred in a number of sets of parallel members and that some of these sets crossed. Grooves with these characteristics could not be explained as exposures of simple sedimentary layers or as abrasion features.

Another early suggestion was that the grooves represent tidal stretching of Phobos. Many of the grooves visible in the early images were oriented in such a way that they could have been formed by tides, but subsequent images of the complete surface eliminated this explanation also.

It became clear that the patterns of grooves are closely related to the largest crater, Stickney, which is about 10 kilometers in diameter, more than a third the length of the satellite. It appeared that the impact might have fractured Phobos and that the grooves are the surface manifestation of fissures.

THE CORNELL STUDIES AND WHAT THEY SUGGEST

A detailed map of the grooves, craters, and other surface features of Phobos and a necessarily less detailed map of Deimos, for which the picture coverage was less comprehensive, were produced at Cornell as a major part of the work for a doctoral dissertation in geological sciences. The dissertation was prepared by one of us (Peter Thomas); the other (Arthur Bloom) was chairman of the supervising faculty committee that also included Joseph Veverka of the Department of Astronomy, who is a member of the Viking Orbiter Imaging Team.

A simplified version of the map of grooves on Phobos is shown in Figure 3. This is an approximation of a Mercator projection, with 0° longitude, 0° latitude being the sub-Mars point, and with longitude measured westerly from 0° to 360°. The two smaller maps are of the north and south polar regions, with 0° longitude being the sub-Mars point. Mapping a strongly elliptical shape (the axial radii of Phobos are 13.5, 10.8, and 9.4 kilometers) on a spherical projection proved challenging and difficult. A degree of longitude along the "equator" ranges in length from 235 meters at 0° to 189 meters at 90°. The length of a degree of lati-

Figure 3

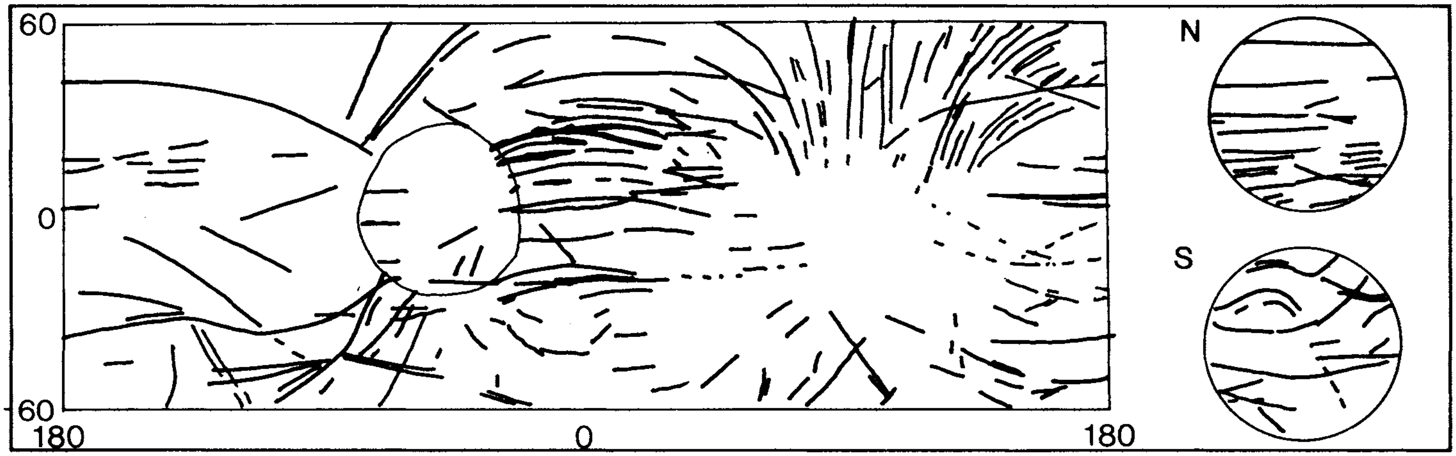


Figure 4

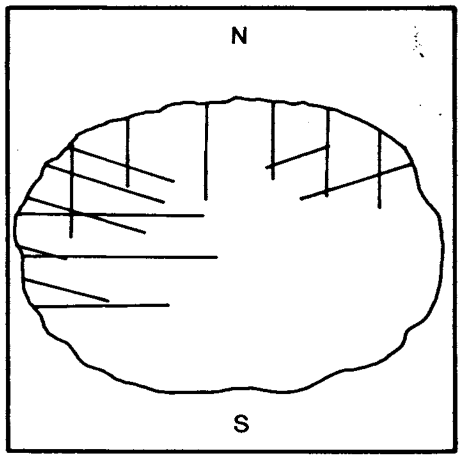


Figure 3. Sketch map of the grooves on Phobos. The small sketches show the north and south polar regions, respectively. This mapping was done at Cornell as part of Peter Thomas's doctoral work in geological sciences.

Figure 4. Four sets of prominent groove planes, as viewed from the trailing side of Phobos. The positions of the planes were determined by geometric analysis of the grooves.

tude also varies with longitude. A peculiarity of such an odd-shaped object is that a perpendicular to the elliptical surface may be as much as 15° away from "straight down" with reference to the center of gravity.

The map demonstrates that the grooves radiate from the crater Stickney, which is near the equator and about 45° east of the sub-Mars point. Geometric analysis of the grooves shows them to be intersections of parallel planes with the surface of the potato-shaped planetoid (see Figure 4). The regular pattern of the planar features suggests that the grooves are the surface expression of cracks, extending deep into the interior, that were produced by the same impact that formed the crater.

Supporting information comes from studies of terrestrial craters produced on Earth by meteorites and nuclear explosions. An empirical equation has been derived that relates depth of fracturing to true crater depth. When a similar relationship is applied to crater Stickney, the depth of fracturing beneath the crater is calculated as 8.5 kilometers, almost half way through Phobos. Although the scaling factors are large, the analogy at least hints at massive fracturing of Phobos. Estimates of the impact energy required to create a crater the size of Stickney also support the theory of massive fracturing. The estimated impact energy, 10^{26} ergs, is about one million times the energy that would be required to propagate about two hundred large fractures in a rock mass the size of Phobos.

Assuming that the grooves are the surface expression of deeper fissures, a further inference can be drawn from the map. The *orientations* of the groove-planes seem more closely related to the ellipsoidal shape of Phobos than they are to crater Stickney. This suggests that the impact caused massive fracturing along planes of preexisting weakness that are systematically related to the shape of Phobos. In other words, Phobos is probably a fragment of some larger object that broke along intersecting planes parallel to some of the later-developed fractures now visible as surface grooves.

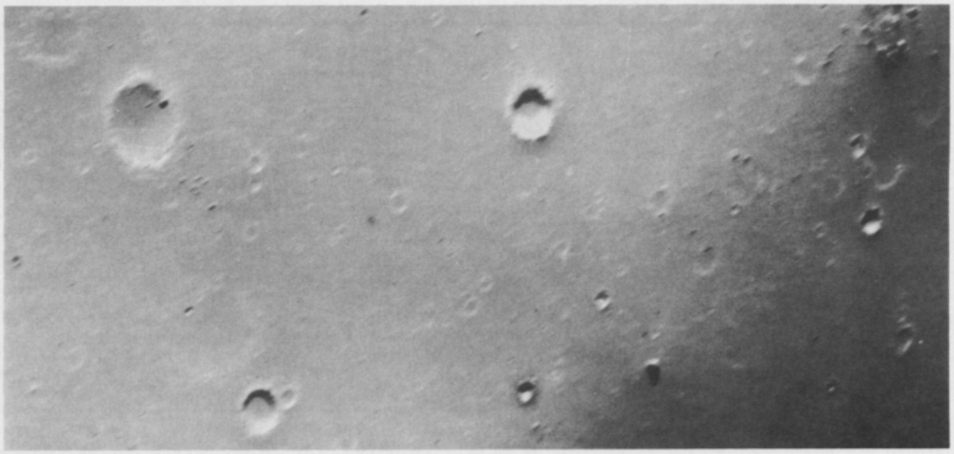


Figure 5. Deimos, as imaged from Viking Orbiter 2 in 1977 from a distance of 50 kilometers. (See also the picture on page 5.) No grooves like those of Phobos are seen, but there are some features that have no counterpart on Phobos. These are the bright streamers near the crater rims, probably debris from the craters, and some large blocks, probably debris thrown out by crater impacts. The area pictured is about 2 kilometers across.

The theory also provides an explanation for the fact that in close detail (see Figure 2d and 2e), the grooves on Phobos are seen to be lines of coalesced pits. Open fractures could have allowed surface detritus to pour down into them until they were nearly full, creating lines of pits similar to those seen in deposits of sand from which material is being withdrawn from beneath.

Another possible explanation of the grooves is that they are the result of the ejection, by steam, of loose material lying on the surface above the fractures, rather than the result of drainage into cracks. Phobos's inferred composition includes much combined water, which may well have been driven off as steam by the impact that formed Stickney.

THE DIFFERENT FACE OF THE SATELLITE DEIMOS

After the close flybys of Phobos revealed the puzzling grooves, a major question was whether Deimos would also be found to have grooves. If Deimos did prove to have a surface appearance similar to that of Phobos, this might be an indication that grooves are a common feature of small bodies in the solar system and might be expected to occur on many asteroids. In October, 1977, Viking Orbiter 2 made a series of close passes by Deimos. Four good-quality images taken from a distance of about 50 kilometers showed objects as small as 3 meters across, but did not show any grooves. Neither did any of the other images obtained during the flyby.

Although Deimos lacks grooves, it does have some prominent features not seen on Phobos (see Figure 5). These include some bright streamers that are apparently very thin layers of debris moving slowly downslope from crater rims. Also visible are numerous scattered blocks, apparently thrown out of impact craters. The craters on Deimos are commonly nearly filled with sediment, which is probably also debris from impacts. Evidently Deimos has retained much more of the debris thrown out of impact craters than Phobos has. This is puzzling because Deimos has a smaller escape velocity (less than 10 meters per second) than Phobos. Perhaps the explanation is that Deimos and Phobos are composed of different material, so that on Deimos debris from impacts would be thrown out with less velocity. Another possibility is that because of Phobos's proximity to Mars, ejected debris might be permanently lost through interaction with the Mars atmosphere, while the more distant Deimos might be able to slowly sweep up debris temporarily lost but still in orbit around Mars. This problem, although still unresolved, can be approached both by theoretical work on the orbits of debris ejected from the satellites, and by experimental studies of impact cratering in materials similar to those believed to form Phobos and Deimos.

SOME BROADER IMPLICATIONS OF WHAT WE HAVE LEARNED

The images from the Viking Orbiter spacecraft have shown that the two moons of Mars are strikingly different in appearance, even though they have spent most, if not all, of their histories in close proximity and are probably composed of similar material. This situation suggests interesting possibilities for the study of asteroids. Most asteroids are small, irregularly shaped bodies, and close-up images of them should show which features on the Martian satellites are due to proximity to Mars and which are due to low gravity. Some data suggest that Phobos and Deimos may once have been asteroids themselves, and the variety of features on these two small satellites suggests that asteroids may well have a very wide range of surface features and histories, since they have occupied a far wider range of environments than have the Martian moons.

A spacecraft mission to an asteroid is, in fact, more likely to take place than one for the purpose of further imaging or possibly sampling Phobos. Asteroids and comets are the two major classes of solar-system objects that have not yet been investigated at close range. Furthermore, spacecraft could land on their surfaces easily because of their low gravity, whereas for a landing on a Martian satellite, much of the planet's gravitational pull would have to be overcome. A spacecraft intended to land on Phobos would have to carry a considerable load of rocket propellent, but a spacecraft could land on several asteroids over a period of years and return samples to Earth with a relatively modest expenditure of energy.

In Phobos we have found features that are unique in our experience. Future explorations of asteroids and of other small satellites may or may not confirm the uniqueness of Phobos, but they will surely reveal features of equal perplexity and interest.

Peter Thomas (at left) discusses his doctoral work with Arthur L. Bloom, his committee chairman.

Peter Thomas, a research associate at Cornell's Center for Radiophysics and Space Research, carried out a photointerpretive study of the morphology of the Martian satellites as the thesis work for his Ph.D. in geological sciences, awarded last spring. The study, discussed in this article, was based on images of Phobos and Deimos relayed by the Viking Orbiters. In his current postdoctoral research with Joseph Veverka, Thomas is continuing his study of the Viking Orbiter pictures. This work includes an investigation of wind phenomena on Mars.

Thomas received the A.B. degree in geology from Princeton University in 1968 and the M.S. in geology from the University of North Carolina at Chapel Hill in 1973. He hopes to pursue a career in planetology.

Arthur L. Bloom, professor of geological sciences at Cornell, is a specialist in geomorphology. He is best known for his studies of the history and interpretation of sea-level changes and their relation to glacial periods, studies that have involved charting and radiometric dating of coral reefs in the South Pacific and off the coast of Australia. At the present time he is serving as international project leader for the IGCP Sea-Level Project sponsored by UNESCO and the International Union of Geological Sciences. His published works include two books. The Surface of the Earth *(Prentice-Hall, 1969) and* Geomorphology: A Systematic Analysis of Late Cenozoic Landforms *(Prentice-Hall, 1978).*

Bloom received the B.A. degree from Miami University (Ohio), the M.A., with honors, from Victoria University in New Zealand, and the Ph.D. in geology from Yale University. At Yale he was awarded the Silliman Prize for his dissertation defense. He joined the Cornell faculty in 1960 after teaching for a year at Yale.

During his years at Cornell, Bloom has spent leaves as a visiting geoscientist at Yale in 1965, on a Scripps Oceanographic Institution expedition in 1967, and as a Fulbright senior research fellow in Australia in 1973–74. He is a fellow of the Geological Society of America and the recent chairman of that society's Division of Quaternary Geology and Geomorphology. He is also a member of the American Association for the Advancement of Science, Phi Beta Kappa, and Sigma Xi.

CLUES TO AN UNDERSTANDING OF VOLCANISM

by Donald L Turcotte

One of the important contributions of the Apollo, Mariner, and Viking space programs has been to afford a better understanding of our own planet. We have discovered, for example, that ancient Moon rocks contain clues to the geologic evolution of Earth. Similarly, information about ongoing Earth processes, such as volcanism, can be derived from studies of the Moon and of the other terrestrial planets.

The value of this comparative approach is demonstrated by the geologic information available from the lunar studies. While the solar system was created some 4.6 billion years ago, most Earth rocks are only a few hundred million years old: the processes of plate tectonics and weathering are continually changing, destroying, and creating rock, so that none of the primal planetary material survives. These processes do not occur on the Moon, however, and consequently Moon rocks are much older. Their ages have been established as greater than 3 billion years, with some rocks approaching the age of the solar system. These ancient rocks contain information applicable to terrestrial evolution in general, information that the much newer Earth rocks do not provide.

Perhaps some of the problems of volcanism on Earth—such as how hot molten rock, or magma, travels from the depths where it is produced to the surface—will also be resolved through comparative studies. As on Earth, the surfaces of Mars and the Moon, and probably other terrestrial bodies as well, have been formed predominantly by volcanism. The following review of the present state of knowledge about volcanism will show how much we have yet to find out, and may suggest how planetary studies might provide some answers.

OUR KNOWLEDGE ABOUT VOLCANISM ON EARTH

Although volcanoes occur over much of the Earth, many form a regular pattern (see Figure 1). This pattern can be explained in terms of plate tectonics, the hypothesis that the surface of the Earth is composed of a series of plates in relative motion with respect to each other. The interaction between these plates at their boundaries is responsible for such phenomena as mountain building, earthquakes, and volcanism. These surface plates, which float on a layer of hot mantle rock, are formed at mountainous ridges that rise above the sea floor. Along the axis of these ocean ridges new crustal material is made by volcanic processes. Upwelling mantle rock partially melts, as it ascends, because of the reduction in pressure; and since this molten rock is less dense than the residual mantle rock, it migrates to the surface to form oceanic crust. But surface plates are consumed as well as created. The plates that are formed from hot mantle rock at ocean ridges travel, bend, and descend back into the mantle at ocean trenches. When a descending plate reaches a depth of about 125 kilometers, volcanoes occur; lines of active volcanoes are found parallel to the ocean trenches. This type of volcanism is attributed to frictional heating on the fault separating the descending plate from the overlying rock.

One example of volcanoes formed at plate boundaries is the chain of vol-

An active volcano on Earth is Mt. Shishaldin on Unimak Island in the Aleutians.

canoes in the western United States, extending from Mount Baker in Washington to Lassen Peak in California. Although the trench with which the chain is associated is virtually filled with sediments, it has been clearly defined by seismic studies. Subduction, the process by which a plate descends back into the mantle, is still occurring at this trench, and therefore the chain of volcanoes may be considered still active. Crater Lake in Oregon is part of this chain. Only eight thousand years ago it was created by a catastrophic eruption that destroyed the preexisting Mount Mazama and generated an estimated seven to nine cubic miles of ash.

Volcanoes adjacent to ocean trenches are, indeed, characterized by extremely violent eruptions that can cause widespread death and destruction. Gas clouds from the eruption on May 8, 1902, of Mount Pelee on the Caribbean island of Martinique killed some forty thousand people in or near the coastal town of St. Pierre. The massive eruption of Krakatoa on August 27, 1883, occurred on an uninhabited island in the strait between Java and Sumatra, but the tidal waves that were generated killed some thirty-six thousand persons. The large eruption on the Aegean island of Santorin in about 1450 B.C. was accompanied by tidal waves, earthquakes, and ash falls, and is believed to be the origin of many legends appearing in Greek literature and the Old Testament; many believe that this eruption destroyed the Minoan civilization on Crete and was responsible for the legend of the lost continent of Atlantis.

In addition to causing disastrous local effects, large eruptions are known to affect climate on a worldwide basis because of the large quantities of ash that enter the atmosphere. The Laki eruption in Iceland in June, 1783, reduced the mean temperature in Europe several degrees for several years. The Krakatoa eruption, in which an estimated five cubic miles of ash was discharged, has been cited as the cause of disastrous crop failures in the northern United States during a year in which there was a frost every month. Some authors associate massive ash eruptions with the onset of ice ages.

Figure 1

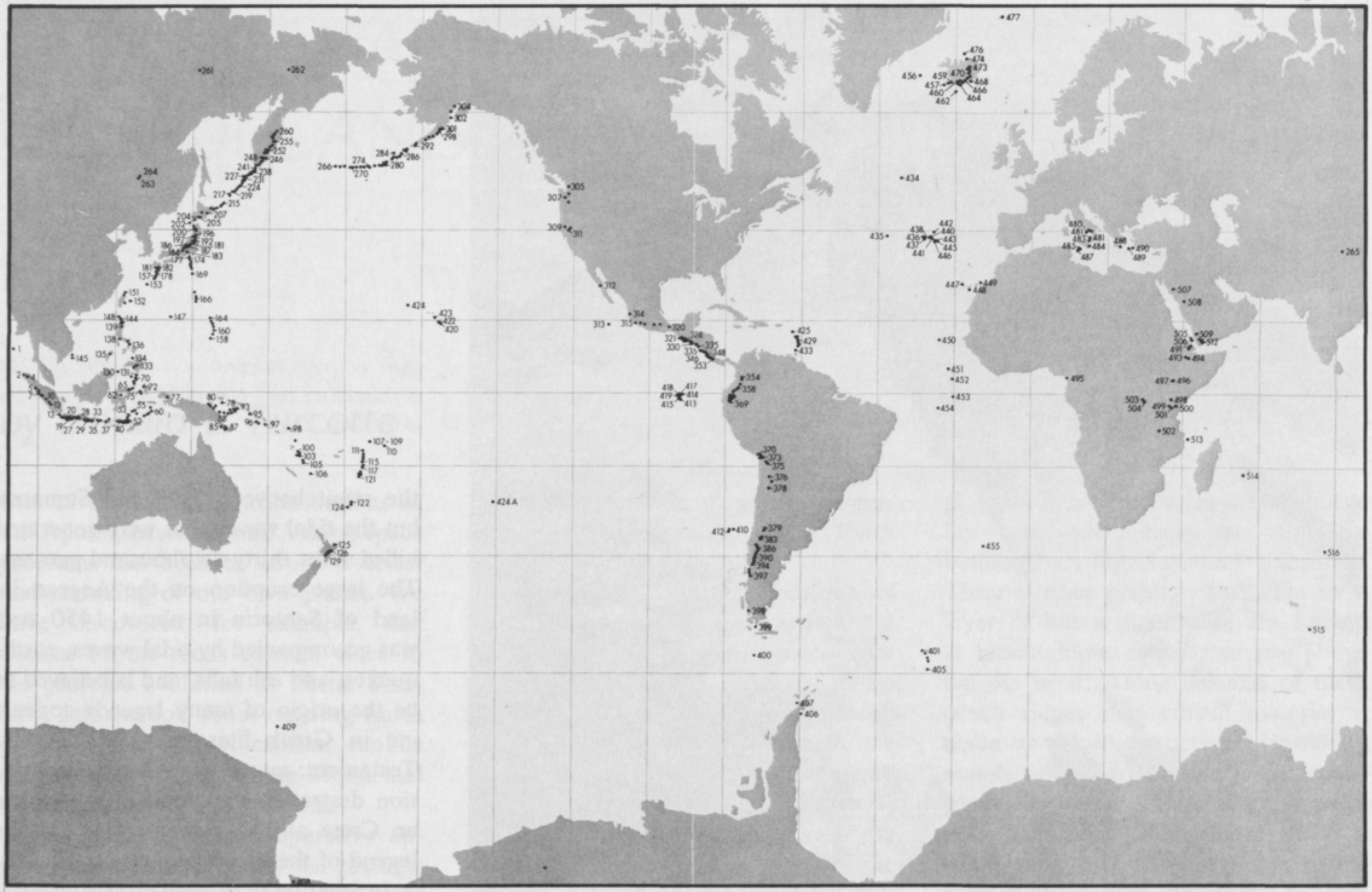


Figure 1. The distribution of volcanoes on Earth. The black marks indicate the locations of known active volcanoes. Many are concentrated in the "ring of fire" that encircles the Pacific Ocean and corresponds to tectonic plate boundaries. Undoubtedly, many more active volcanoes lie undiscovered on the sea floor, particularly along the ocean ridges.

Although plate tectonics explains a great many features of volcanism, there are a number of exceptions. The active volcanoes in the Hawaiian Islands occur at the end of a chain of extinct volcanoes extending across the Pacific Ocean near the center of a plate. Extensive intraplate volcanism also occurs throughout much of Africa. Since this kind of volcanism cannot be explained by the subduction process that takes place at the edges of plates, other explanations have been proposed. One is that there may be a crack in the plate that allows magma to reach the surface. Another suggestion is that the plate is sound, but an ascending, plume-like flow of magma simply pushes its way through.

An interesting anomalous region is an area in western United States where extensive volcanism has occurred over the past seven million years (see Figure 2). This area is so broad that the volcanism cannot be directly related to a plate boundary. It appears that the region is being broken apart and that magma reaches the surface through the cracks. A particularly extensive series of volcanics that covers the Snake River plain (see Figure 3) is similar to the volcanics that make up the lunar seas (see Figures 4 and 5).

Figure 2

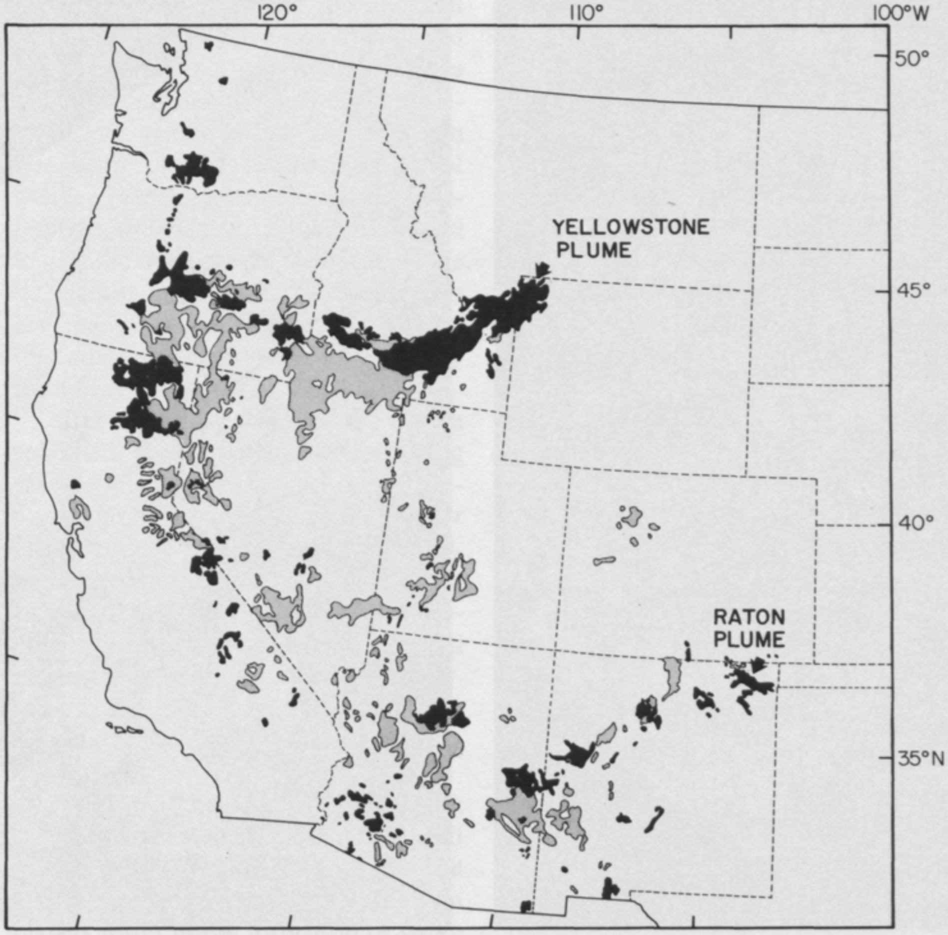


Figure 3

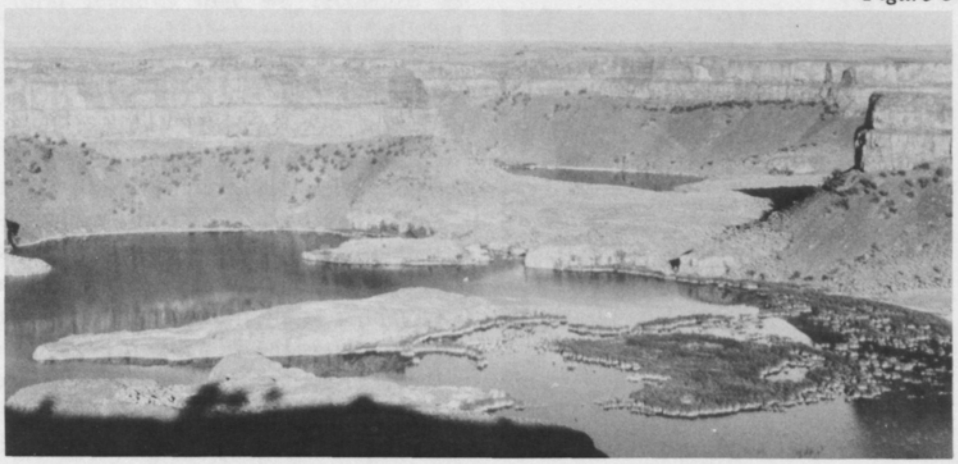


Figure 2. Volcanic regions in the western United States. The shaded areas represent regions that are covered with volcanic rocks between 1.5 and 7 million years old; the dark areas correspond to regions with volcanic rocks less than 1.5 million years old. The most extensive of these more recent volcanics is the Snake River plain; the volcanics grow progressively younger to the east, culminating in the very recent volcanic rocks of the Yellowstone area. The volcanics in this region are unusual for Earth. It appears that magma has flowed out through numerous cracks over a wide area rather than erupting to form discrete constructional volcanoes.

Figure 3. A view of a Snake River reservoir with the flat volcanic plain beyond.

There are many aspects of Earth volcanism that are poorly understood. Although it is known that the magmas that reach the surface originate at depths of five to fifty miles, or in some cases even deeper, the way or ways in which the material reaches the surface is unclear. Also, little is known about the causes of the spacing of the volcanic edifices or the episodicity of eruptions. Much remains to be discerned about the mechanisms of volcanic processes.

Figure 4

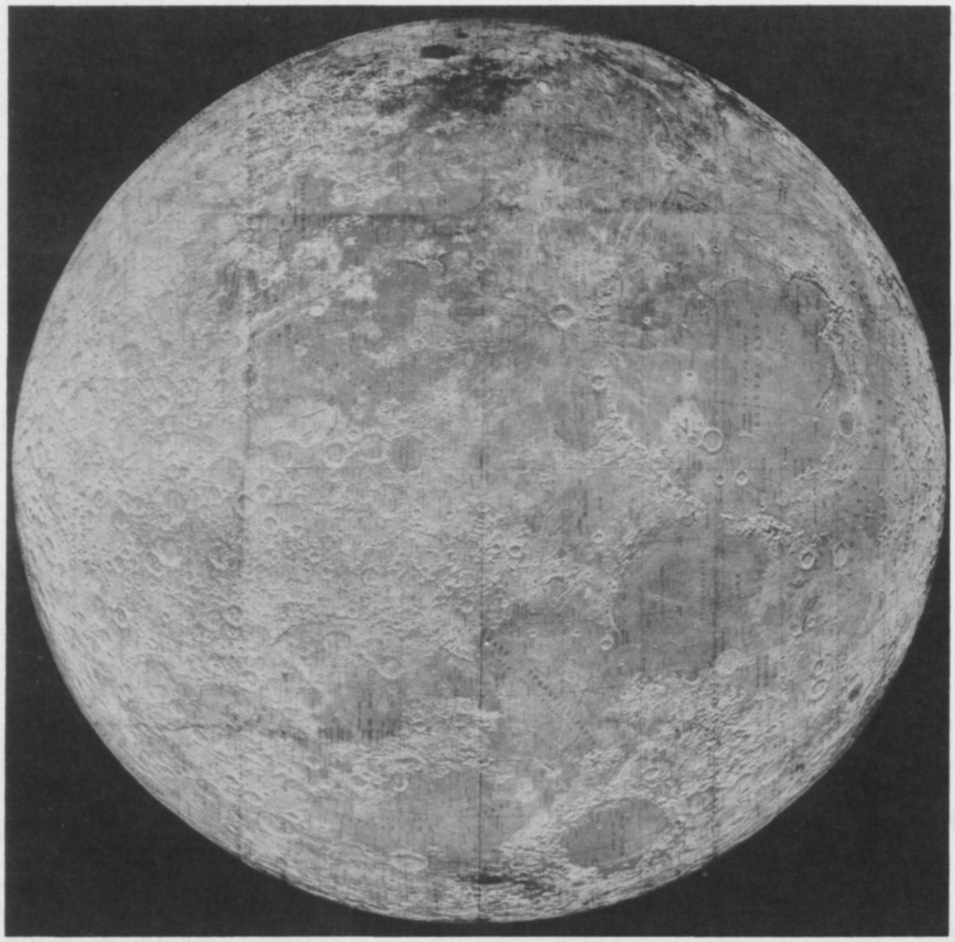


Figure 5

Figure 4. The lunar surface, showing highlands and mare (from a Rand McNally map). The darker open areas are the mare, which are the remains of volcanic flows that occurred 3 to 4 billion years ago.

Figure 5. The lunar mare Nubium, as photographed at the Lick Observatory.

THE VOLCANISM OF EARTH'S MOON

Prior to the Apollo missions it was recognized that the Moon is made up of two types of terrain, the highlands and the mare (seas). To the naked eye the mare are the dark regions. Their extent is shown in Figure 4.

The early Apollo missions showed that the lunar mare are composed of dark, fine-grained volcanic rocks very similar to those that make up the oceanic crust on Earth. Radioactive dating showed that these volcanic flows occurred between 3 and 4 billion years ago. The later Apollo missions concentrated on studies of the lunar highlands, which are composed of a different kind of volcanic material. These highland rocks are much more complex, since they have been considerably altered by extensive meteoritic impacts, and dating has shown that they have an almost uniform age of 4.5 billion years, nearly the 4.6 billion year age for the solar system that has been obtained from studies of meteorites.

As a result of extensive studies, it

has been concluded that the highland rocks are the remnants of a solidified magma ocean that covered the surface of the Moon at the time of its formation. The theory is that as the Moon was being created by the collision of smaller planetary bodies, called planetesimals, sufficient energy was dissipated to heat the outer part of the Moon above its melting point. The highland rocks are the scum that formed the top of this magma ocean and subsequently solidified.

After the outer shell of the Moon solidified, collisions with the remaining planetesimals continued to occur, creating large circular depressions or basins on the Moon's surface. Subsequently some of these large basins on the near side of the Moon became almost filled with the dark, fine-grained magmas to form the nearly level surfaces of the lunar mare. Thus extensive magma flows rather than raised volcanoes were formed.

There are considerable similarities between these flows on the Moon and those of the Snake River plain. The question of why some volcanic flows on planets result in the formation of structural features that we recognize as volcanoes and others result in flat-lying flows remains largely unanswered. Possible explanations are that the magmas have different viscosities, or that they flow to the surface at different rates, or that there is a combination of these factors.

The cause of the mare volcanism is not clearly established, either. It may have resulted from a heating of the lunar interior by the decay of radioactive elements. As the volcanism occurred, the magmas would have carried the decaying radioactive isotopes into

Figure 6(a)

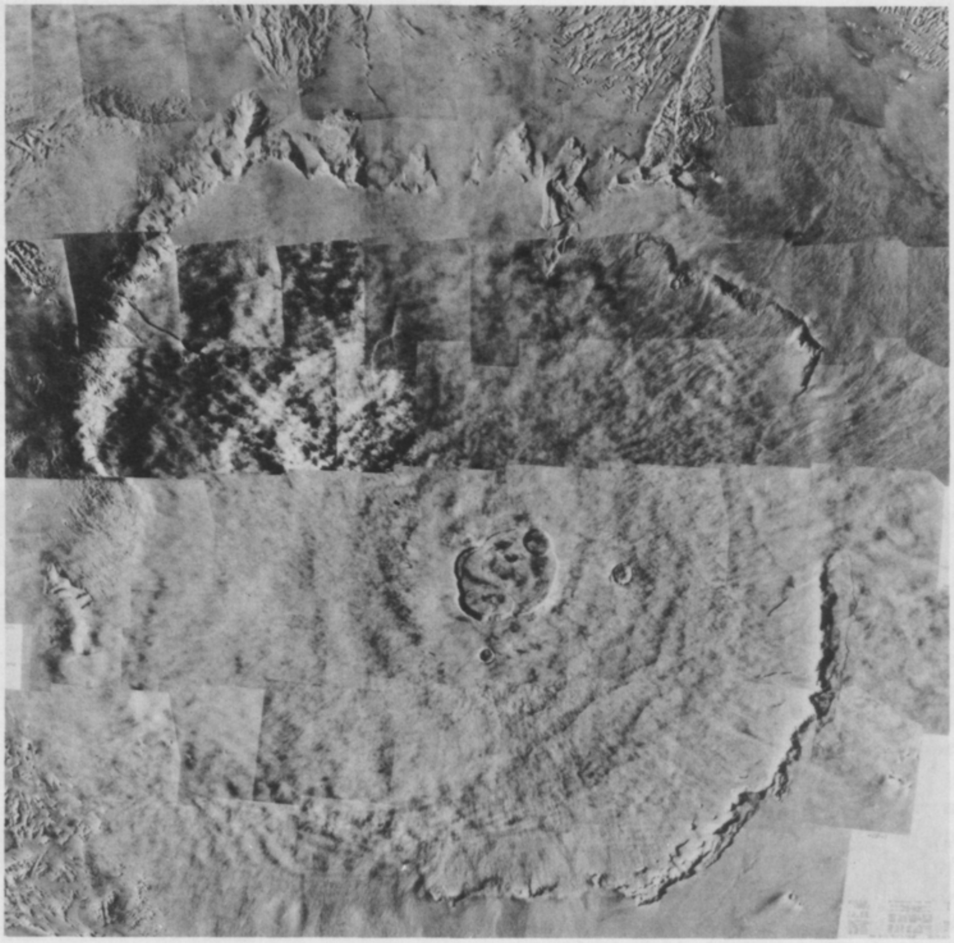


Figure 6(b)

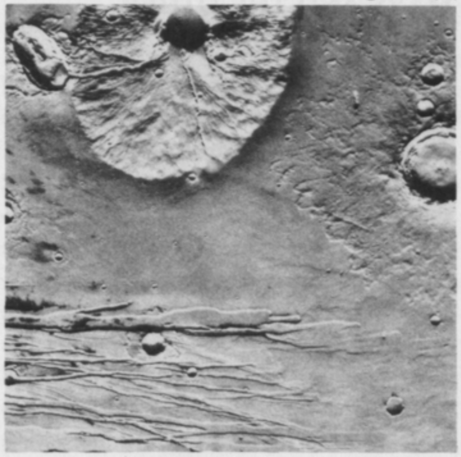


Figure 6. Volcanic edifices on Mars, from images taken on the Viking missions. (a). Olympus Mons, the largest volcano on Mars, is three times the height of any volcano on Earth. It rises more than 24 kilometers above the surrounding plain and the crater is 80 kilometers across.

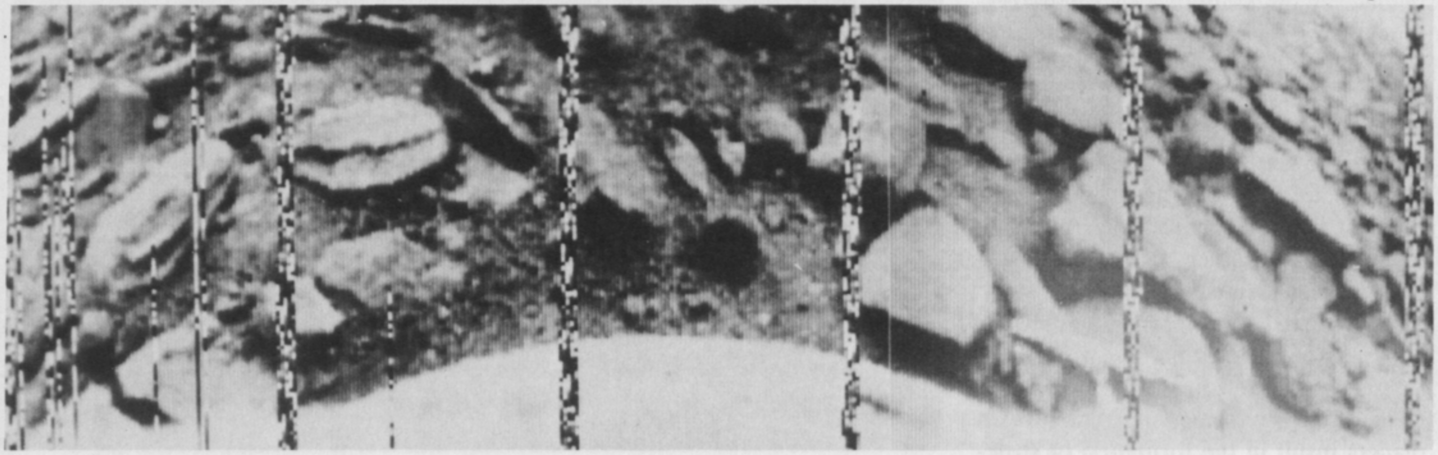
(b). Another volcano on Mars, Ceraunius Tholus, rises about 5 kilometers above the plains and is about 100 kilometers across. A flow from the volcano has apparently filled part of the impact crater at the base. This volcano is on the northern margin of the Tharsis bulge and volcanic province.

Figure 7

Figure 7. A Mariner 10 image of Mercury. This surface resembles the lunar highlands.

Figure 8. Venus, as imaged by a Soviet lander in 1976. The most notable feature is the abundance of large boulders on the surface.

Figure 8



the lunar crust; the generated heat would have been effectively removed by conduction to the surface, and the removal of the radioactive materials would have prevented further heating of the lunar interior. Certainly there has been an almost complete absence of volcanism on the Moon for the last 3 billion years. Unlike the Earth, the Moon is a quiescent body. This is verified by the almost total lack of earthquakes as recorded by the seismographs installed during the Apollo mission.

MARS AND THE OTHER TERRESTRIAL PLANETS

One of the most important results of the Mariner 9 mission to Mars was the discovery of massive volcanic edifices. The largest, Olympus Mons, is about three times as high as the highest volcano on Earth. The reason for the greater height is not completely understood. Presumably the smaller surface gravity field on Mars is a factor, but the chemistry and strength of the rock and the "plumbing system" of the volcano may also be involved. Until there are sample returns from Mars, there is little chance of a real understanding of the volcanic processes on that planet.

Mercury appears to have no features that cannot be explained in terms of our understanding of the Moon. Images taken by Mariner 10 (see Figure 7) indicate a surface similar to that of the Moon, but without the mare basins.

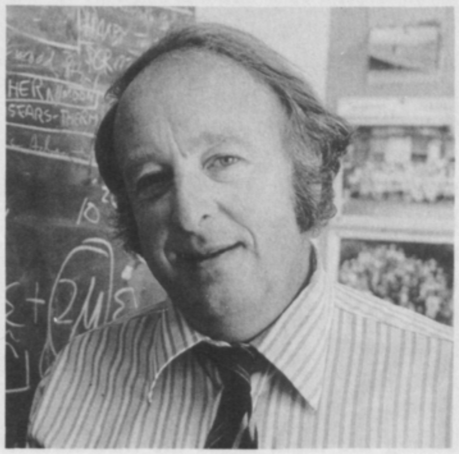
Venus is a particularly interesting planet because its size is similar to that of Earth. Plate tectonics would be expected—if there is no system of crustal plates it will be a considerable surprise

"The entire science of volcanology has received remarkably little attention."

—and so would volcanism. Very little is known at the present time, however. Images of the surface returned by a Soviet lander (see Figure 8) show only the presence of angular boulders. Of much greater promise is a proposed United States mission that will use radar photography to provide surface imagery similar in quality to the pictures of Mars.

THE NEED FOR EXPANDED STUDIES OF VOLCANISM

The entire science of volcanology has received remarkably little attention. This is surprising in view of the powerful and often devastating effects caused on Earth by the forces of volcanism. We are better able to anticipate volcanic eruptions than we are to predict earthquakes, because major eruptions are almost always preceded by a period of extensive seismic activity (earthquakes) in the immediate vicinity of the volcano. Nevertheless, catastrophic volcanic eruptions pose one of the major threats to our civilization. There is ample evidence that the climatic change due to a massive eruption can cause



one or more crop failures on a worldwide basis, and for this reason alone, a better understanding of volcanic processes should have a high priority.

What is needed is a program of research, both theoretical and experimental, based on observations of the Earth and its solar system neighbors. When we understand the fundamental processes of volcanism and their place in the geologic evolution of the terrestrial planets, we will be better prepared to deal with their manifestations on Earth.

Donald L. Turcotte, professor of geological sciences, is a specialist in geomechanics and geophysical fluid dynamics. He has conducted research on thermal and fluid convection in both the Earth and the Moon.

Turcotte came to Cornell in 1959 as a member of the aerospace engineering faculty and moved to the Department of Geological Sciences in 1973, after developing a research interest in the geological aspects of fluid dynamics. He holds a baccalaureate degree in mechanical engineering and a doctorate in aerospace engineering, both from the California Institute of Technology, and a Master of Engineering (Aerospace) degree from Cornell. He taught for a year at the United States Naval Postgraduate School before joining the faculty here.

His publications include Space Propulsion *(Blaisdell, 1965) and, as coauthor,* Statistical Thermodynamics *(Addison-Wesley, 1963). He is a fellow of the Geological Society of America and a member of the American Physical Society, the American Geophysical Union, and the Seismological Society of America.*

COLD SKIN AND A WARM HEART: A MODEL FOR EARTH'S MOON

An Interview with Arthur F. Kuckes

The moon may seem to be a cold, dead body, but actually it has a hot interior beneath a relatively thin insulating outer layer. This view, contrary to the opinion of many scientists, is held by Cornell professor Arthur F. Kuckes, who bases his model on magnetometer, gravity, and heat-flow measurements made as part of the Apollo program. Kuckes' study of the Moon, which complements his terrestrial research, was discussed in an interview with the *Quarterly* editor.

Why are geophysicists interested in the Moon's interior?

Studies of the similarities among bodies in space can help us understand planetary constitution, evolution, and formation. Study of the Moon's properties as related to comparable Earth properties has revealed a great deal about both bodies and about the geophysics of such planetary bodies in general.

How can the interior of the Moon be studied experimentally? What data have been obtained, and how?

As part of the Apollo program, many instruments were placed on the Moon's surface at different locations and times, and continuous measurements from these stations have been radioed back to Earth, along with simultaneous measurements from orbiting satellites. I have been particularly interested in the magnetometer measurements; some of the best date from the Apollo 12 mission in 1969. Very good data were received from the magnetometers during the first lunar day (equivalent to fourteen Earth days). Unfortunately, during the lunar night the instruments evidently were damaged by the extreme cold and we never got very good data after that. What we did receive, together with data from later missions, provided us with much information.

The basic idea is to measure how the magnetic field associated with the solar wind is affected by the presence of the Moon, and from this to deduce information about the electrical conductivity and therefore also the temperature of the Moon's interior.

My first studies of magnetic field transients focused on comparisons of magnetic field intensities and fluctuations as recorded simultaneously by the Apollo 12 magnetometer on the lunar surface and a second instrument carried by Explorer 35 orbiting the Moon (see Figure 1). The penetration of temporal changes of the magnetic field into the lunar interior is limited by Lenz's law—that is, by the induction of eddy currents in the lunar interior. This limited field penetration can be deduced by noting the slow change of the radial magnetic field transient (B_{Ax}) on the lunar surface compared to the same transient observed in the orbiting satellite (see Figure 2). The field change as a function of the period of the transient is shown in Figure 3.

While it is generally agreed that this field amplification is due to the finite electrical conductivity in the lunar interior, there has been much controversy about interpreting these data in detail. A problem arises because the relation between the conductivity as a function of depth and the observed field amplification is not unique. One simple model (which I proposed) that fits the data is that of a uniformly conducting interior below a depth of about 160

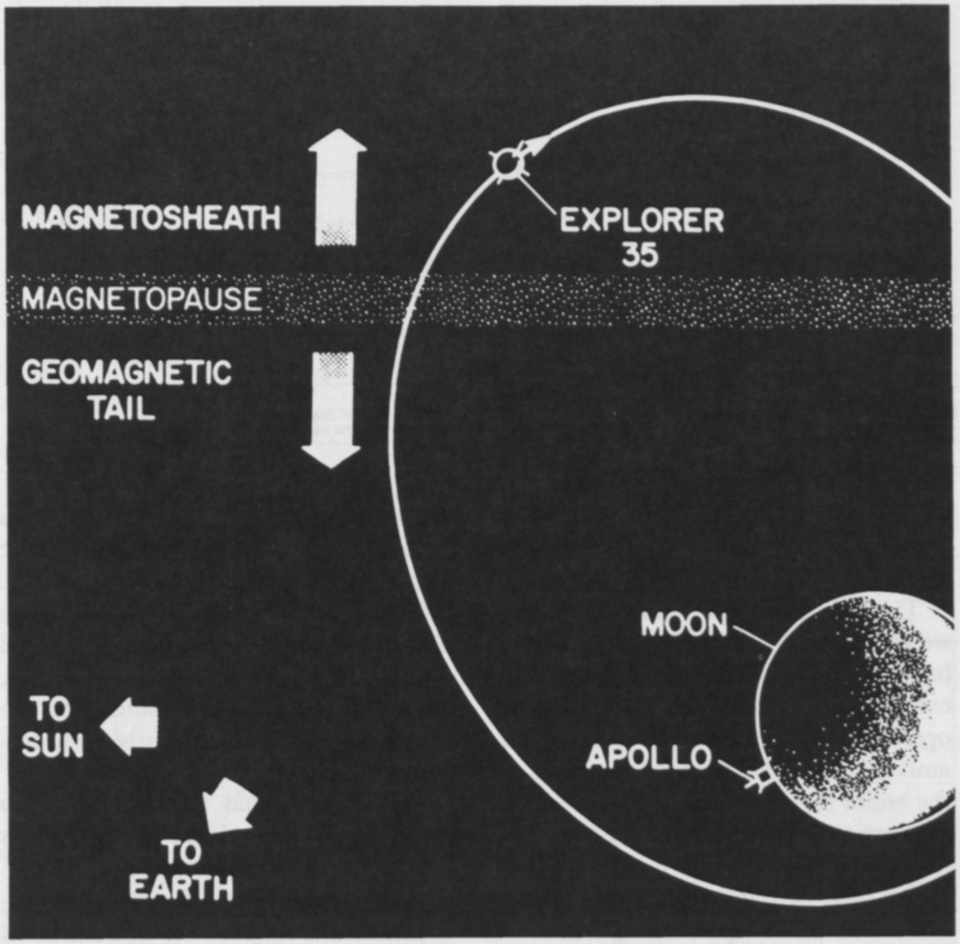


Figure 1. Lunar magnetometer measurements. The diagram shows the relative positions of the Explorer 35 orbit and the Apollo 12 instrument on the Moon's surface.

kilometers and a perfectly insulating skin above this depth. The conductivity for the interior is still small compared to many standards—for example, it is about five thousand times smaller than the conductivity of sea water.

How can we learn about the geophysics of the Moon from these data?

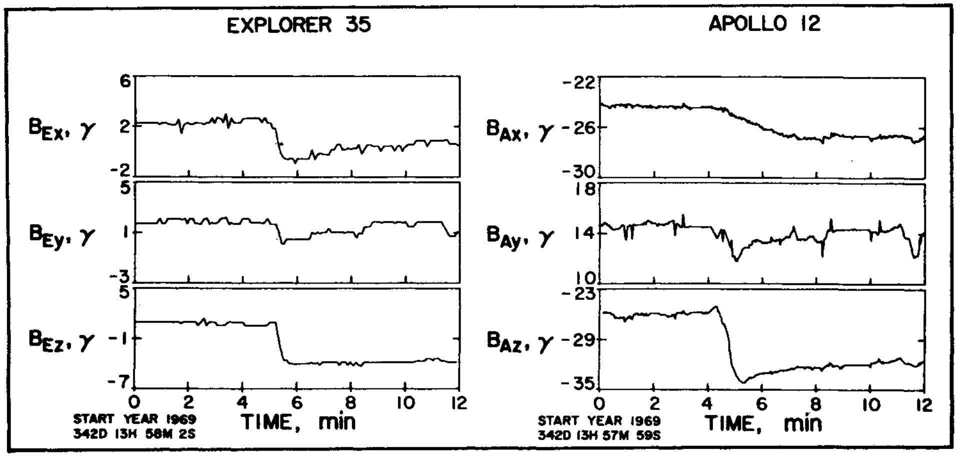
The electrical conductivity of rock-forming silicates varies very strongly with temperature in a way that is very similar to the behavior of semiconductors. The intrinsic mechanism for turning these ceramic-like materials into electrical conductors is by the thermal activation of charge carriers to form "conduction bands." Thus, even though we cannot be sure of the exact composition of the lunar interior, we do have considerable confidence that the conductivity has the characteristic temperature dependence of a thermally activated process.

Another contribution I made was to recognize that just the shape of the graph of field amplification versus period of the transient field (shown in Figure 3a) is significant. The shape of the graph, combined with our knowledge of the intrinsically strong variation of silicate conductivity with temperature and the widely held view that the composition of the lunar interior must be quite uniform, leads to very important statements about how temperature can vary with depth. Figure 3 shows that the experimental data allow relatively little uncertainty in the profile of temperature versus depth when these raher simple and generally accepted assumptions are applied to the data directly. While electrical conductivity versus depth is not a particularly interesting quantity in itself, *temperature* versus depth is extremely important since it is temperature and heat that are the dominant parameters governing the evolution of a planetary body.

The conclusions to which the graphs shown in Figure 3 lead are that the temperature below a depth of not more than 200 kilometers must be rather uniform and that any temperature gradient in the outer part of the Moon must be limited to this thin outer skin. What is the temperature of the interior? If we

Figure 2. Typical nighttime transient response magnetic field data. A transient measured by an Apollo lunar surface magnetometer while on the nighttime (antisolar) side of the Moon is shown with simultaneous external solar wind field data measured by Explorer 35. The x axis is directed radially outward from the lunar surface; the y and z axies are tangential to the surface, directed eastward and northward, respectively. The slow change of the radial field component on the lunar surface (B_{Ax}), as compared to the change recorded in space by Explorer 35 (B_{Ex}) is indicative of a conducting lunar interior.

Figure 2



take the magnitude of the conductivity implied by the observations, together with laboratory measurements of the conductivity of olivine (considered the most likely candidate for the lunar interior), we calculate a temperature of about 1,200°C for the lunar mantle. This is very close to the temperature that is believed to exist in the corresponding part of Earth's mantle.

Likewise, the conclusion that a strong lunar temperature gradient is essentially limited to an outer thin skin is reminiscent of information we have about the Earth. A widely accepted view is that in the Earth there is a significant amount of heat generated in the deep interior by the continuing radioactive decay of radiogenic elements, among other processes. This heat must escape if the Earth is to be kept from melting. The deep interior remains hot enough, though, so that the material is slightly plastic and can move slowly, like a tar, at rates measured in centimeters per year. Such slow movement, or convection, is a very effective mechanism for the transfer of heat. In the brittle outer skin of the Earth, however, heat transfer can proceed only by thermal conduction, which is in general much less effective.

The principles are similar to those we encounter in keeping a house warm in winter. The amount of heat that can escape by convection through a single open window can be more than the amount conducted through the walls of the entire house. In the Earth, the slow convection is effective in moving heat from the interior, where it is generated, to the base of the thermal lithosphere. Only a small temperature gradient is required. But the final transfer to the Earth's surface by conduction through the rigid thermal lithosphere requires a temperature difference of about 1,200°C across the 70- to 100-kilometer thickness.

The picture that emerges is of a Moon with a hot interior, very much like Earth's deep mantle, encased by a thin insulating thermal lithosphere.

What does this picture suggest about the origins of the Earth and the Moon?

We know that to one-third of one percent, the rock of which the Moon is made has the same average density as the Earth's mantle. It is probably similar in composition to that portion of Earth. In fact, a widely held view is that the Moon originated as a chunk of mantle material thrown out from the Earth, or else that the Earth's mantle and the Moon formed simultaneously by accretion from the same cloud of matter.

It is known that the Moon has no central iron and nickel core, as does the Earth, or at most a very small one. This is evident from density measurements and also from the measurement of total moment of inertia, which does not easily fit the model of a Moon with an iron core. The model of the Moon with a hot, convecting interior of quite uniform temperature and composition is consistent with the considerations of lunar mass and rotation.

What are the objections to this interpretation of the experimental data?

An important argument against the conception of the Moon as essentially a two-layer body consisting of a uniform hot, plastic interior encased by a thin rigid outer skin is that the lunar

Figure 3(a)

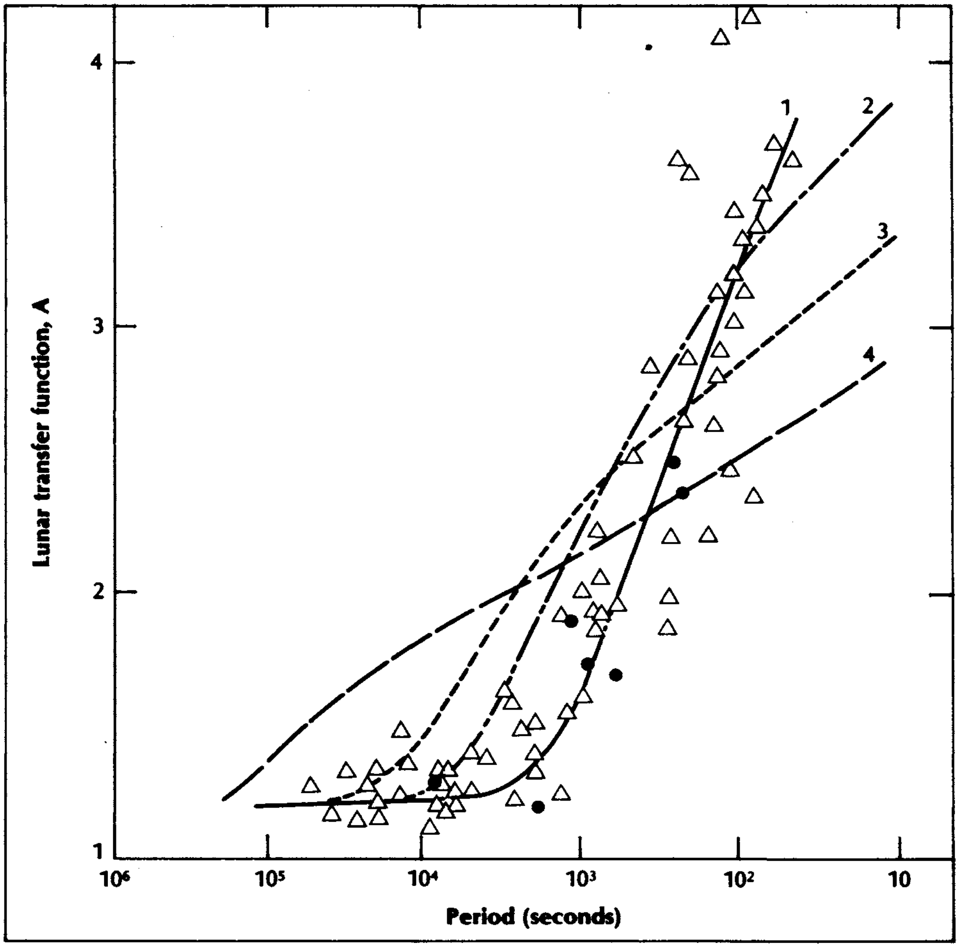


Figure 3(b)

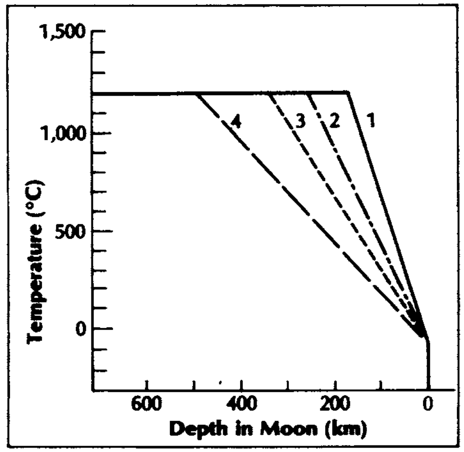


Figure 3. Experimental data and theoretical profiles for the variation of temperature with depth in the Moon's interior.

(a) shows field amplification data obtained from the Apollo mission magnetometer measurements; the experimental points (● from radial field nighttime data and △ from horizontal field daytime data) were obtained by simple Fourier analysis of magnetic transients in the Explorer 35 and Apollo 12 magnetometer records.

The theoretical curves 1 through 4 were generated from the corresponding theoretical profiles, shown in (b), of temperature as a function of depth. The temperature range in (b) is from surface temperature (the point common to all the profiles) to the maximum internal temperature.

Since the fit is best for curve 1 and becomes progressively less satisfactory as one goes from 2 to 4, this figure shows rather clearly that the temperature variation occurs within the depth range corresponding to curve 1 or possibly curve 2. This means that only the outer portion of the Moon—to a depth of about 200 kilometers—can have a significant temperature gradient.

lithosphere must have much strength, since the Moon is so much farther from mechanical equilibrium than is the Earth. The gravity field of the Earth is that of a plastic body in rotational equilibrium to a few parts in one hundred thousand. The gravity field of the Moon is about one hundred times farther from such an equilibrium state. Also, the lunar mare basins have large mass excesses, called mascons, associated with them. These mascons were discovered to have large gravity anomalies which significantly perturbed the orbiting satellites in the Ranger series of missions prior to the Apollo program.

The gravity field of Earth is much more uniform than its topography might suggest (the continental surface of the Earth stands about 5 kilometers above the floor of the oceans). If the continental platform mass were effective in generating gravity perturbations, the gravity field of the Earth would be nonuniform to several parts per thousand rather than to several parts per hundred thousand. But because the continents are, in fact, "floating" in the

Figure 4

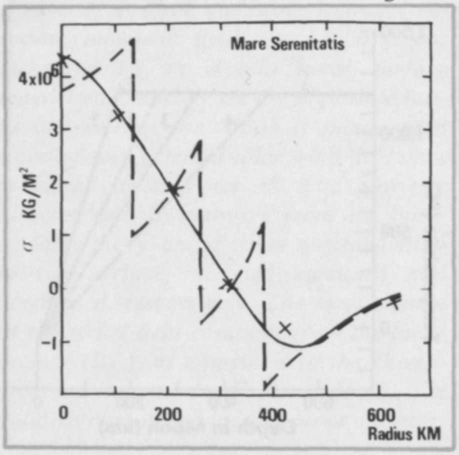
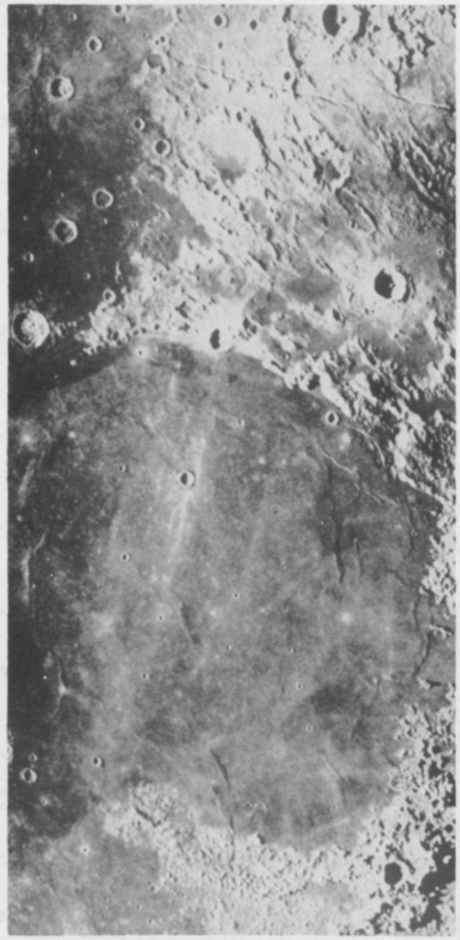


Figure 4. The best fit of a theoretical curve to experimental data (crosses) on density in the region of a lunar mascon. Values of σ, the net excess surface mass per unit area, are plotted versus radial distance from the center of the mare. The jumps in the theoretical line (dotted) are due to computational jumps in the simple loading function used and should be "smoothed out" to form the solid curve shown.

The theoretical curve shown—the one that fits the data—corresponds to an elastic lunar lithosphere 54 kilometers thick. Professor Kuckes' model of the Moon, based on electrical conductivity data, shows a thermal lithosphere of about 200 kilometers, a .thickness that is in accord with the derived elastic lithospheric thickness.

It may be noted that the gravity data from satellite measurements show that the area of excess density associated with a mare is surrounded by a smaller area of somewhat less than normal density. As shown in this figure, the relative magnitudes of the positive and negative values of σ are approximately as expected from the theory.



Right: Mare Serenitatis, as photographed at the Lick Observatory.

Earth's plastic mantle rather like icebergs floating in the ocean, the gravity field of the Earth is very uniform and close to that of a rotating fluid drop in gravitational equilibrium with itself. In general, most terrestrial gravitational perturbations that do exist are generated by mass excesses which are supported elastically by the Earth's outer 25 to 30 kilometers of rock (the elastic lithosphere). Studies of the crustal flexure of mass excesses—such as volcanic cones—reveal that over periods of significant geologic time, only the outer 25 to 30 kilometers of the Earth is rigid enough to support excess masses without slowly creeping. This high-temperature mechanical creep is the same phenomenon that severely limits, for example, the performance of aircraft turbine engines. The net result is that the Earth is very round and the gravitational perturbations are limited to small values over regions a few hundred kilometers, at most, in extent.

Since the Moon is much further from being "round" and has the large mascons, it was argued that there must be a strong elastic lithosphere. It was pointed out that this would be incompatible with the thin lithosphere suggested by the electrical data.

How can these difficulties be resolved?

To answer these criticisms, I undertook a detailed study of the overall lunar gravity and of the mascon perturbations in the context of the model indicated by the electrical analyses. The idea was to find out how thick the elastic crust would have to be to account for the Moon's nonequilibrium shape and to provide enough support for the mascons. I found that in both cases independently, the results led to the deduction of a lithospheric thickness in good harmony with that suggested by the electrical data and also in harmony with analogous studies of the Earth.

The crustal flexure study of the mascons made use of the rather detailed gravity maps of the Moon that have been prepared by analyzing the doppler shift of the microwave signals used for communicating with orbiting satellites. My procedure was to use these gravity maps to compute values for σ, the net excess surface mass per unit area of various mascons. After averaging in azimuthal angle around a mare basin, these values were plotted as a function of radial distance from the center of the mare. Next, curves were computed for the theoretical response of elastic layers of various thicknesses to a range of applied loads, and the curve with the best fit to the experimental data was selected. The fit for Mare Serenitatis is shown in Figure 4; in this case the thickness of elastic lithosphere indicated by the crustal flexure theory is about 54 kilometers. Of particular significance in making the theoretical calculation is the ring of negative gravitational compensation that surrounds a mascon: the "wavelength" of this region effectively determines a flexure thickness.

Correspondences between the Moon and the Earth become apparent. The magnitude of shear stress required by the model for support of the Serenitatis mascon (about 1,000 atmospheres of force/area) is very similar to the stress in the Earth's lithosphere which the support of Hawaii requires. Another comparable measurement is the ratio of elastic thickness to the thickness of the total thermal lithosphere: for the Moon the derived elastic thickness of 50 to 70 kilometers is about one-third the 200-kilometer thickness derived for the thermal lithosphere; for Earth the absolute values are smaller but the ratio is about the same.

An analysis of the nonspherical lunar shape yielded similar crustal thicknesses and similar shear stress levels (slightly less than 1,000 atmospheres of force/area). Thus the objections to my model that are based on considerations of crustal strength are not objections at all, but actually lend further support to the conclusions made in the magnetometer studies.

In view of the similarities, how do you explain the differences in the surface appearance and behavior of Earth and Moon?

One of the reasons for the stable mechanical state of the Moon's surface is that mechanically the Moon is a much stronger body than the Earth. The appropriate parameter describing surface rigidity is four hundred times larger for the Moon than it is for the Earth. (I believe that the Earth's lithosphere is thinner than that of the Moon because the Earth is larger and more heat per unit surface area must be dispersed.) Another factor that greatly influences the rigidity of the lunar lithosphere is the lower gravity of the Moon—an element of mass on the Moon is subjected to only one-sixth the gravity force it would experience on Earth. In addition, since the radius of the Moon is four times smaller, the lateral distance over which loads have to be supported is less.

The relative mechanical rigidity of the two bodies is demonstrated both experimentally and theoretically by the fact that the Earth is more nearly spherical. Large bodies in space tend to be very spherical because the amount of material that has mechanical integrity (the brittle shell) is relatively small: the body is able to adjust itself to the spherical shape in response to the overwhelming forces of gravity. The Earth's deviation from the spherical is only a few parts in 10^5. The Moon, with its stronger surface and lower gravity, can afford to be much farther from a perfect sphere.

Evidence of surface mechanical instability is, of course, quite evident on Earth. The crust is divided into plates that are in continuous movement, accompanied by continuous processes of mountain building and ocean trench formation. But on the Moon, the topography is essentially the same today as it was billions of years ago. Linear features such as mountains and trenches are absent. Mascons appear to be lava flows from this early period (although some people who believe that the Moon is and always has been cold consider the mascons to be material compacted as a result of impact heat from meteorites). Except for the accumulation of impact craters, the surface features established 3 to 4 billion years ago have remained unchanged because of the lack of water and an atmosphere and therefore of erosion.

Has the study of the lunar rock samples contributed information useful in constructing a model of the Moon?

It has been shown that the chemical processes operating during the evolution of the Moon and of the Earth are analogous, except for differences caused by the absence of water on the Moon. (The water, expelled because of the intense heat, was lost because of the low gravity.)

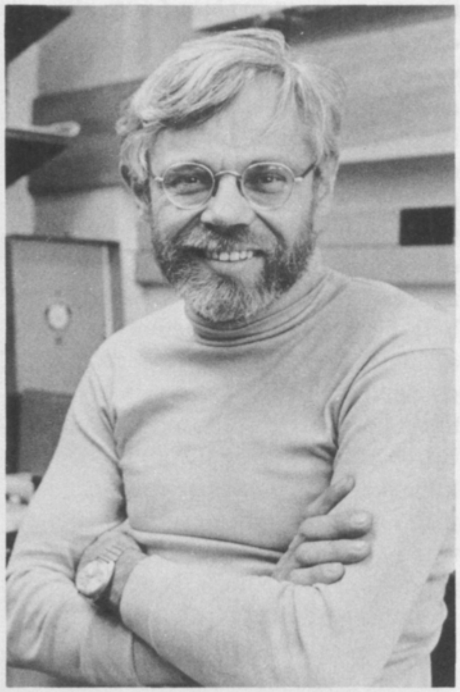
On Earth radioactive material has been brought to the surface by the continuing convective forces and concentrated there. On the Moon there is also an enhanced surface concentration of radioactive materials. The lunar heat flow has been determined from the temperature gradient with depth, measured in lunar drill holes; it turns out to be much less than it would be if the interior had as much radioactivity as the surface rocks. This would suggest that the evolution of the Earth and of the Moon involved similar processes of heat generation and convection. Of course, some scientists favor the idea that the radioactivity in the Moon rocks was caused by a "sprinkling" of radioactive material from supernova explosions. However, the total heat generation per unit volume in the Moon is about the same as in the Earth's mantle.

Which planets or satellites appear to be the best subjects for convection studies? What projects would you like to see initiated?

One important advantage of the Moon for doing electrical conductivity measurements is the absence of water, which greatly complicates similar measurements on Earth. The Earth also has a complex ionosphere to deal with. Nevertheless, Earth studies are obviously important; in fact, I am currently concentrating my efforts on that aspect of the overall problem.

Similarity studies involving other planets are also under way and can be expected to yield useful information. Magnetic fluctuation studies of Mars would be particularly interesting because that planet, like the Earth, is known to be tectonically active. At present there is great interest in doing crustal flexure studies on Mars and several magnetometer experiments have been planned. Studies of the Venusian lithosphere would also be interesting; since the surface of Venus is very hot, the effects of creep and the inability of the surface to carry loads should be dominant if our current ideas are correct. It has been proposed to extend the Moon studies by providing for simultaneous observations from several station magnetometers on the surface; another proposal is to use a lunar orbiter at a very low altitude—50 kilometers or so—instead of ground stations so that conductivity maps could be made. The present-day lack of new "starts" on planetary missions has greatly restricted these projects.

Of course, the applicability of Moon studies to an understanding of Earth is greater if we can assume that their formation and evolution are analogous. I feel that the information we have so far indicates that despite the great differences in external features, our planet and its natural satellite are close relatives.



Arthur F. Kuckes, professor of applied physics and a specialist in geophysics and plasma physics, has been conducting research on convection in the Moon since the Apollo data began to be received on Earth. He is also investigating the crustal structure of Earth using electromagnetic sounding techniques.

Kuckes received the B.S. degree in physics from the Massachusetts Institute of Technology in 1953. Upon graduation, he received a Fulbright scholarship to study for a year in Göttingen, Germany, and then a National Science Foundation fellowship for a year's study in Paris. He completed the work for a doctorate in physics from Harvard University in 1959 and then served as a member of the plasma physics research staff at Princeton University until he joined the Cornell faculty in 1968. He spent two years on leave from Princeton at the Culham Laboratory for Plasma Physics in England and a year on leave from Cornell at the Goddard Space Center and at Oxford University in England.

In 1971 he received the Excellence in Engineering Teaching Award, presented each year to a Cornell professor by the Cornell Society of Engineers and Tau Beta Pi.

He is a member of the American Geophysical Union and the American Physical Society.

REGISTER

■ The College will be greeting the new year with a new dean. *Thomas E. Everhart,* professor and department chairman in electrical engineering and computer sciences at the University of California, Berkeley, has been nominated as Cornell's seventh dean of engineering. The appointment, subject to approval by the University's Board of Trustees, is expected to be effective January 1.

Everhart will replace Edmund T. Cranch, who became president of Worcester Polytechnic Institute this fall. Andrew Schultz, Jr., dean from 1963 to 1972, has been serving as acting dean.

A specialist in electron optics and electron physics, Everhart holds the A.B. degree in physics (magna cum laude) from Harvard University, the M.Sc. in applied physics from the University of California at Los Angeles, and the Ph.D. in engineering from Cambridge University, England, where he was a Marshall Scholar and did research on the scanning electron microscope. He has been at Berkeley since receiving the doctorate in 1958.

In 1974–75 Everhart was awarded a Guggenheim fellowship and spent the year at Cambridge and at Waseda and Osaka Universities in Japan. In 1966–67 he spent a leave at the Institüt für Angewandte Physik in West Germany as a National Science Foundation senior postdoctoral fellow.

Throughout his career he has been active as an industrial consultant in such fields as microwave electron tube development and the application of electron beams to semiconductor analysis and fabrication. Organizations he has worked with include Hughes Research Laboratories, Westinghouse Research Laboratories, Ampex Research and Development Laboratories, and the Watkins-Johnson Company.

Everhart is a fellow of the Institute of Electrical & Electronics Engineers and a member of the Electron Microscopy Society of America (which he served as president in 1977), the Microbeam Analysis Society, the American Association for the Advancement of Science, Phi Beta Kappa, Sigma Xi, and Eta Kappa Nu.

He and his wife, Doris, have four children ranging in age from fifteen to twenty-two.

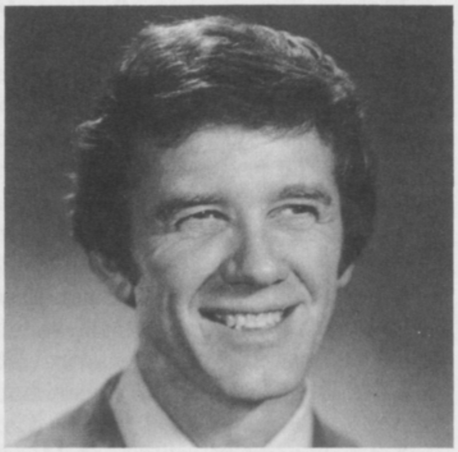
Everhart

■ Administrative appointments at the College of Engineering this year include a school director and two department heads. *Richard N. White* is the new director of the School of Civil and Environmental Engineering, succeeding Walter R. Lynn. *Arthur H. Nilson* is chairman of the Department of Structural Engineering in that school, replacing Richard H. Gallagher, who is now dean of the College of Engineering at the University of Arizona. *Arthur L. Ruoff* is director of the Department of Materials Science and Engineering, succeeding Robert W. Balluffi, now at the Massachusetts Institute of Technology. All three appointees have five-year terms.

White, a structural engineer, is a specialist in model analysis, earthquake engineering, and concrete structures, including shells, reactor structures, and framed structures. He joined the Cornell faculty in 1961 after three years of teaching at the University of Wisconsin, where he studied for B.S., M.S., and Ph.D. degrees in civil engineering. His experience includes consulting for a number of industrial and government organizations, and employment as a

White

Nilson



Ruoff

practicing engineer; he is a registered professional engineer in New York State. At Cornell he has been in charge of the Structural Models Laboratory for sixteen years, and is currently a member of the graduate Field of Nuclear Science and Engineering, as well as the graduate Field of Civil and Environmental Engineering. He has been honored as co-recipient of the Collingwood Prize of the American Society of Civil Engineers, he was elected a fellow of the American Concrete Institute, and at Cornell he received the 1972 Chi Epsilon Professor of the Year award and the 1965 Cornell Society of Engineers–Tau Beta Pi Excellence in Teaching Award. He is co-author of a widely used series of texts on structural engineering, and has published numerous professional papers.

Nilson, a specialist in the behavior and design of structural concrete, has been a member of the faculty here since 1956. He was acting chairman of the department in 1973–74 and for several years was graduate faculty representative for the Field of Civil and Environmental Engineering. His degrees are the B.S. from Stanford University, the M.S. from Cornell, and the Ph.D. from the University of California at Berkeley. In addition, he is registered as a professional engineer in Connecticut and New York and has had professional experience as a civil and structural engineer. He was elected a fellow of the American Concrete Institute and received that society's Wason Medal for materials research in 1974. He has been awarded National Science Foundation Science Faculty and Danforth Foundation Teachers Fellowships, and in recent years has held lecturing and research appointments at Manchester and Salford Universities in England and at Politecnico di Milano in Italy. He is author of the text *Design of Prestressed Concrete*, just released, and co-author with George Winter of *Design of Concrete Structures*, which is internationally recognized as the standard work on that subject. Nilson's special research interests have included finite element analysis, prestressed concrete members, concrete subject to multi-axial stress states, and the properties and behavior of ultra-high-strength concrete.

In addition to being appointed department director, Ruoff has been named the Class of 1912 Professor. He is known especially for his research on high-pressure phenomena—he has reached pressures of 1.4 million atmospheres and made surfur and xenon metallic—and also conducts research on the deformation of solids. He joined the faculty here in 1955 after earning the B.S. degree at Purdue University and the Ph.D. in physical chemistry at the University of Utah. At Cornell he has served as graduate faculty representative for the Field of Materials Science and Engineering, and he is a member also of the graduate Fields of Applied Physics and of Geological Sciences. He has twice served on the executive committee of the University's Materials Science Center and currently is active in the National Research and Resource Facility for Submicron Structures, both as a researcher and as a member of the program committee. Outside the University he serves as a consultant to numerous industries and laboratories on high-pressure phenomena and to several universities on techniques of multimedia instruction, an alternative he has explored in classes here. His honors have included a National Science Foundation Science Faculty Fellowship and the 1967 Western Electric Fund Award, presented by the American Society for Engineering Education for excellence in instruction of engineering students. Also, he was elected a fellow of the American Physical Society and was named Engineer of Distinction by the Engineers Joint Council.

■ Several academic units are being administered this year by acting heads. At the School of Applied and Engineering Physics, *Terrill A. Cool* is acting director; *Richard H. Lance* is acting chairman of the Department of Theoretical and Applied Mechanics; and *Richard W. Conway* is acting chairman of the Department of Computer Science.

Cool has been at Cornell since 1965, when he joined the thermal engineering faculty after completing his graduate studies. Subsequently he transferred to the applied and engineering physics faculty, and has served as graduate faculty representative in that field. His degrees are the B.S. from the University of California at Los Angeles and the M.S. and Ph.D. from the California Institute of Technology. A specialist in chemical physics, his research is centered on molecular lasers.

Lance is an associate dean of the College and co-director of the Engineering Cooperative Program, as well as associate professor of theoretical and applied mechanics. His administrative responsibilities are in the area of industrial liaison, and his teaching and research are in the areas of plasticity, inelastic behavior of solids, and numerical methods in engineering. Lance has been a member of the mechanics faculty since 1962, and previously served as acting department chairman as well as graduate faculty representative. His degrees are the B.S. from the University of Illinois, the M.S. from the Illinois Institute of Technology, and the Ph.D. from Brown University.

Conway studied at Cornell for both the B.S. degree and the Ph.D. in operations research and joined the engineering faculty here in 1956. He has participated in the establishment of the Department of Computer Science and the University's Office of Computer Services, which he directed for two years. He has served as faculty representative for the graduate Field of Computer Science and is a member of the graduate Field of Operations Research. His specialty area is the development, operation, and management of information systems. He is a coauthor of several books in his field.

■ Nonacademic administrative personnel appointed at the College in recent months include an assistant dean, *Ron W. Simmons,* and two assistant directors of admissions, *Mariea T. Blackburn* and *Arthur A. McCombs.*

Simmons' primary responsibilities are with minority students enrolled in the College, and include supervision of special activities and services, liaison with University groups with functions specifically related to minority students, participation in the College admissions process, and fund-raising efforts for special programs. He holds the B.A. degree in history and political science from the University of Hartford, and M.S. and Ed.D. degrees in education from the University of Massachusetts. In previous positions he has been an elementary school teacher and principal in Connecticut, a professor of education and department chairman in the New Jersey state college system, and an associate professor of education at Lockhaven State College in Pennsylvania.

Blackburn's special areas of responsibility in the admissions office are in the selection of transfer students and the administration of the College's undergraduate financial aid program. She received the B.A. degree in English from Wilkes College, Wilkes-Barre, Pennsylvania, and the M.S. in educational administration from Syracuse University, where she worked for a year as assistant director of admissions. For the past four years she has been an admissions officer at the State University of New York at Oswego.

McCombs, who joined the staff here last fall, is primarily responsible for minority-student admissions, including the identification and selection of candidates. He holds the B.A. degree in political science from the College of Wooster and the M.A. in student personnel and higher education from Columbia University. His experience includes a year as assistant dean of students and residence halls coordinator at East Stroudsburg State College (Pennsylvania) and as student affairs counselor at the State University of New York Agricultural and Technical College at Farmingdale. He also taught black history at Farmingdale.

The directors of Cornell's two new national research centers conferred with visitors at an open house this fall. Above: Edward D. Wolf (at center), director of the National Research and Resource Facility for Submicron Structures, discusses the new laboratory with G. Conrad Dalman (at left), director of Cornell's School of Electrical Engineering, and Robert R. Fossum, director of the Defense Advanced Research Projects Agency.

Below: Boris W. Batterman (at left), director of the Cornell High Energy Synchrotron Source, conducts a tour of the Wilson synchrotron for Richard C. Atkinson, director of the National Science Foundation.

■ Two recently initiated research centers at Cornell are headed by College of Engineering professors. *Boris W. Batterman* is the director of the Cornell High Energy Synchrotron Source (CHESS), which is now under construction with funding from a $1 million National Science Foundation grant. The director of the National Research and Resource Facility for Submicron Structures (NRRFSS) is *Edward D. Wolf,* whose appointment was announced last spring.

CHESS, a radiation laboratory to be operated in conjunction with the Cornell Electron Storage Ring (CESR) at the Wilson synchrotron laboratory, will provide a source of high-energy x rays for basic research. These x rays, which are emitted in synchrotrons as "by-products" of particle accelerators, have become recognized only recently as valuable for studies of the basic properties of matter. CHESS is expected to be used by physicists, materials scientists, chemists, crystallographers, and medical researchers throughout the United States for investigations of the structure of a wide variety of materials. It will be useful, for example, in studies of enzymes, biologically important proteins, crystals, and heavy atoms. CHESS is expected also to augment the NRRFSS facilities for project work on the development of submicron electronic components.

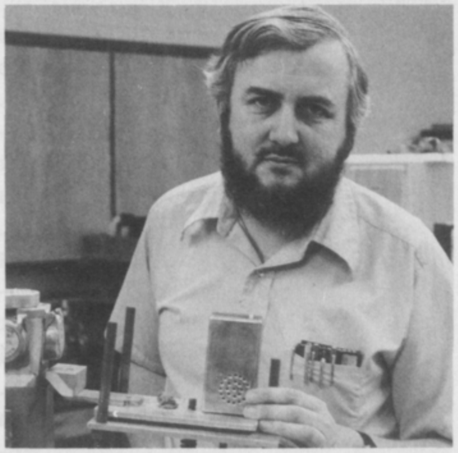
Batterman, a specialist in solid-state physics who has concentrated his recent research on x-ray and neutron diffraction for studies of atomic arrangement, has been at Cornell since 1965 as a member of both the applied and engineering physics and the materials science and engineering faculties. He resigned as director of the School of Applied and Engineering Physics in order to assume his new position. He holds baccalaureate and doctoral degrees from the Massachusetts Institute of Technology and has had experience in industry as a member of the technical staff of Bell Telephone Laboratories and as a consultant. He is a fellow of the American Physical Society and has held Guggenheim and Fulbright fellowships for study and research in Germany and Italy.

■ Tenured faculty appointments have been made in two schools of the College of Engineering. *William A. Bassett* was named professor of geological sciences, effective in January, 1978, and *Michael S. Isaacson* was appointed associate professor of applied and engineering physics, effective in December, 1978.

Bassett, speacialist in the use of high-pressure techniques as applied to earth materials, is especially recognized for his contributions to the development of diamond cell pressure techniques and instrumentation. His research is relevant to current work in the Department of Materials Science and Engineering as well as the Department of Geological Sciences. He came to Cornell from the University of Rochester, where he was a member of the geological sciences faculty for sixteen years, and he has also been a research associate at the Brookhaven National Laboratory. His degrees, all in geology, are the B.A. from Amherst College and the M.A. and Ph.D. from Columbia University. He is a fellow of the Geological Society of America and the Mineral Society of America, and a member of several other professional and honorary societies.

Isaacson, a specialist in electron optics and diffraction, received the 1976 Burton Award from the Electron Microscope Society of America for outstanding contributions by a scientist under the age of thirty-five. He came to Cornell from the University of Chicago, where he was an assistant professor in the Department of Physics at the Enrico Fermi Institute and the College. He holds the B.S. degree (with highest honors) in engineering physics from the University of Illinois at Urbana, and the S.M. and Ph.D. degrees in physics

Bassett



from Chicago. After receiving his doctorate, he spent two years as a staff scientist at the Brookhaven National Laboratory. He is a member of the American Association of Physics Teachers, the Electron Microscopy Society of America, the Radiation Research Society, the Biophysical Society, and Phi Eta Sigma.

■ Assistant professors were appointed in four schools and departments. They are *Thomas D. O'Rourke* in civil and environmental engineering, *Franklin Luk* and *Fred B. Schneider* in computer science, *David T. Grubb* in materials science and engineering, and *Robert G. Bland, Jeremy A. Bloom,* and *Thomas Boucher* in operations research and industrial engineering.

O'Rourke, a specialist in geotechnical engineering, is a Cornell graduate; he received the B.S. degree in civil engineering here in 1970. He took his graduate work at the University of Illinois, earning the M.S. degree in 1973 and the Ph.D. in 1975, and subsequently served as a member of the faculty there. His honors include election to Tau Beta Pi, Chi Epsilon, and Sigma Xi, and he was co-recipient in 1976 of the C. A. Hogentogler Award of the American Society for Testing and Materials.

Luk received his Ph.D. in computer science from Stanford University in September of this year. His previous degrees are the B.S. in mathematics from the California Institute of Technology and the M.S. in statistics from Stanford. His speciality area is numerical analysis.

Schneider worked at Cornell's Office of Computer Services as a part-time consultant while he was an undergraduate here in electrical engineering and computer science, and he continued in that office in summer work as a systems programmer. He received the B.S. degree in 1975 and then studied at the State University of New York at Stony Brook for the M.S. and Ph.D. degrees in computer science. He specializes in the area of systems. He is a member of the Association for Computing Machinery and the Institute of Electrical & Electronics Engineers.

Grubb was educated at Brasenose College, Oxford, earning the B.A. and M.A. degrees in physics and the Ph.D. degree in materials science and engineering. In 1972–73, after completing his doctorate, he conducted research in the macromolecular research center in Strasbourg as a NATO European fellow, and then he served as a research assistant and associate at Bristol University before coming to Cornell. His specialty area is the study of crystalline polymers, their structure, and the effects on them of radiation damage. He is a member of the Institute of Physics and a fellow of the Royal Microscopical Society.

Bland, a specialist in applied mathematical programming and combinatorics, studied at Cornell for three degrees in operations research and industrial engineering. As an undergraduate he was elected to Tau Beta Pi and Eta Sigma, while in graduate school he held a National Science Foundation fellowship, and recently he was granted a two-year Alfred P. Sloan fellowship to support his current research. After receiving his doctorate in 1974, Bland taught mathematics at the State University of New York at Binghamton; during his years there he spent leaves as a research associate at the Center for Operations Research and Econometrics in Haverlea, Belgium, and as a visiting professor at the European Institute for Advanced Studies in Management in Brussels. He is a member of the Operations Research Society of America and the American Mathematical Society.

Bloom recently completed his graduate studies at the Massachusetts Institute of Technology, earning the S.M. and Ph.D. degrees in operations research. He received the B.S. degree in electrical engineering from Carnegie-Mellon University in 1973. His specialty area is applications of operations research, especially to energy and electronic power systems, and he has served as a summer intern at RCE and as a consultant to Intermetrics, Inc. He is a member of the Institute of Electrical & Electronics Engineers, the Operations Research Society of America, and the Institute of Management Sciences.

Boucher, a specialist in engineering and industrial economics, joined the operations research and industrial engineering faculty here in January, 1978, and completed his doctoral work in industrial engineering at Columbia University in June. He also holds the degrees of M.Phil. and M.S. from Columbia, the M.B.A. in finance from Northwestern University, and the B.S. in electrical engineering from the University of Rhode Island. He has taught at Rutgers and Fairleigh Dickinson Universities, as well as at Columbia. Also, he has worked as a senior project engineer for the Continental Can Company, a staff consultant for the Abex Corporation, and a senior financial analyst for the Otis Elevator Company. From 1965 to 1967 he served as an officer in the U.S. Army Corps of Engineers as an instructor and as a construction project leader.

■ Visiting faculty members and fellows on campus during the fall term include the following.

Applied and Engineering Physics: Jene A. Golovchenko, adjunct associate professor, from Bell Telephone Laboratories; and Michael H. Worthington, visiting professor, from Oxford University, England.

Civil and Environmental Engineering: Richard E. Goodman, visiting professor, from the University of California at Berkeley; Sergio Montes, visiting fellow, from the University of Tasmania; and Anthony J. Richardson, visiting assistant professor, from Monash University, Melbourne, Australia.

Computer Science: Pablo Barrera, visiting professor, from the National University of Mexico, Mexico City; Friedbert Follert, visiting fellow, from Bonn, West Germany; Charles F. Kelemen, visiting associate professor, from Ithaca College; Jorgen Steensgaard-Madsen, visiting associate professor, from the University of Copenhagen, Denmark; and Homer Walker, visiting associate professor, from the University of Houston.

Electrical Engineering: Richard E. Blahut, adjunct associate professor, from IBM Federal Systems Division; and Paul C. Shields, visiting professor, from the University of Toledo.

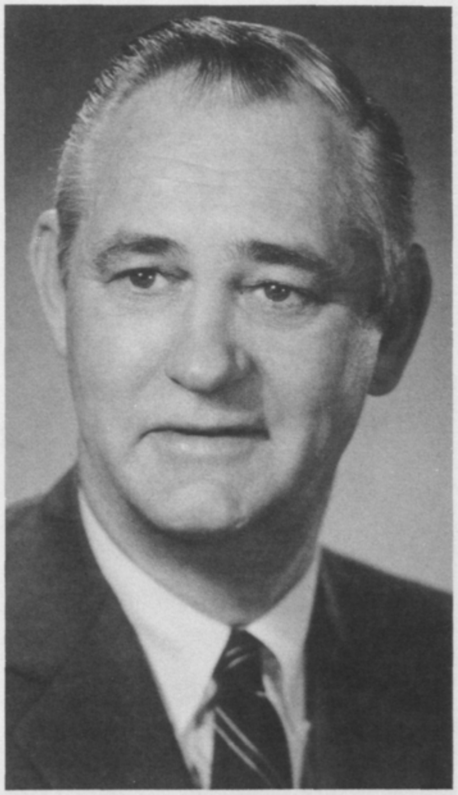
Materials Science and Engineering: Hael Mughrabi, visiting associate professor, from the Max Planck Institute, Stuttgart, West Germany.

Mechanical and Aerospace Engineering: Dale Taulbee, visiting fellow, from the State University of New York, Buffalo.

Operations Research and Industrial Engineering: Iswar Basawa, visiting associate professor, from Latrobe University, Australia; Joshua B. Levy, visiting fellow, from Georgia Institute of Technology; and Alden H. Wright, visiting fellow, from Western Michigan University.

Theoretical and Applied Mechanics: Alan B. Taylor, visiting associate professor, from Oxford University, England.

Kiersch



■ George A. Kiersch retired this past summer as professor, emeritus, of geological studies after an eighteen-year teaching career at Cornell. An internationally known specialist in engineering geology, he has served also as consultant, manager of exploration, or geologist for more than one hundred major engineering works or projects throughout the world. He is continuing his activities as a consultant, and he and his wife are dividing their time between homes in Arizona and in Ithaca, New York.

Kiersch was graduated from the Colorado School of Mines with the degree of Geological Engineer in 1942 and spent the World War II years as an officer in the U.S. Army Corps of Engineers. Subsequently he entered graduate school at the University of Arizona and received the Ph.D. in geology in 1947. During the early part of his career, he was employed as a geologist for a study of lead-copper mines in Arizona, as a geologist for the Underground Explosion Test Program at sites in Utah, as project geologist for California dams constructed by the U.S. Army Corps of Engineers, and as supervising geologist for the International Boundary and Water Commission, investigating three hundred miles of territory adjacent to the Rio Grande for the construction of eight large dams. Later he became a member of the geology faculty at the University of Arizona and had the principal responsibility of directing a survey of mineral resources in Navajo-Hopi Indian reservations in Arizona and Utah. He also spent five years directing a large-scale mineral resources survey of lands in California, Nevada, and Utah for the Southern Pacific Corporation. He is registered as a professional geologist and engineering geologist in Arizona and California.

At Cornell he served as department chairman from 1965 to 1971, while the department was still in the College of Arts and Sciences. During this period the department name was changed from Geology and Geography to Geological Sciences, the study of geophysics was introduced, and an expansion of faculty and the graduate studies program was begun. He served also as graduate field representative and as a member of University boards on traffic control and graduate fellowships.

His publications include more than sixty papers and volumes and 175 technical reports. He served for ten years as an editor of the *Engineering Geology Case Histories* published by the Geological Society of America, and has been on the editorial board of *Engineering Geology Journal* since 1964.

He was elected a fellow of the Geological Society of America and of the American Society of Civil Engineers. He is a member also of the Society of Economic Geologists, the U.S. Committee on Large Dams, the Association of Engineering Geologists, the International Society for Rock Mechanics, and the honorary societies Tau Beta Pi, Sigma Xi, and Theta Tau.

■ Henry David Block, professor of theoretical and applied mechanics, died suddenly on October 6 shortly before he had planned to leave for a sabbatic year at universities in Japan and other parts of the Far East. He was fifty-eight years old and is survived by his wife, Faye, and a son, David.

Block, a specialist in applied mathematics, was a member of Cornell's Center for Applied Mathematics and the graduate Fields of Applied Mathematics and of Computer Science, as well as of the Department and graduate Field of Theoretical and Applied Mechanics. His research interests included biomathematics, artificial intelligence, bionics and robots, the theory of automata, pattern recognition, and environmental systems. For several years he collaborated with the late Professor Frank Rosenblatt in analysis of research results obtained from the Cornell Perceptron, an innovative, pioneering device that served as an effective model of the behavior of brain cells during perception and memory. He had planned to conduct research in Japan on mathematical models of visual perception, directed toward the development of computer vision.

Block began to study engineering at the City College of New York after earning a degree in literature there. He received the B.C.E. degree in civil engineering in 1943 and then worked as experimental flight test engineer, stress analyst, and aerodynamist at the Goodyear Aircraft and the Fairchild Engine and Aircraft Corporations. In 1946 he began graduate study in mathematics at Iowa State University and received the M.S. degree in 1947 and the Ph.D. in 1949. He taught mathematics at Iowa State and at the University of Minnesota before joining the faculty here in 1955.

His honors included a Guggenheim fellowship in 1970–71 for studies in biomathematics. In 1972 he received a citation from *Applied Mechanics Reviews* "for over fifteen years of distinguished science." During his years at Cornell he served at various times as editor of the *SIAM Journal on Computing,* as chairman of the Gordon Conference on Biomathematics (1969–70), and as president of the Research Club at Cornell. In the 1960's he spent a year's leave at the University of California.

Block served as a consultant to a number of companies and research organizations. He was a member of the American Mathematics Society, the Mathematical Association of America, the Institute of Electrical & Electronics Engineers, the Association for Computing Machinery, the Artificial Intelligence Society of Britain, and the honorary societies Phi Beta Kappa, Tau Beta Pi, Pi Mu Epsilon, Phi Kappa Phi, and Sigma Xi.

VANTAGE

Engineering Strength on the Cornell Teams

In athletics, as in academic performance, Cornell depends on its engineers. A co-captain of this year's varsity football team and a large contingent of the players were engineers. So were the varsity soccer co-captains and about a third of that team. ■ *The soccer co-captains were seniors Jim Rice, from Chatham, N.J., and Bob Capener, from Ithaca, N.Y. Rice was named in 1977 to the All-New York and All-Ivy first teams and won an All-American honorable mention. (That year Cornell was Ivy League Champion.) Capener was All-Ivy in 1975 and returned to the Cornell squad this season after two years in Europe.*

Other engineers on the varsity soccer squad were Kurt Bettger, Bill Edwards, Dave Levy, Rod Ruoff, Steve Strandberg, and Rich White. Ruoff's father is Arthur Ruoff of the engineering faculty; his brother Steve, now completing his final year in engineering, was a team member last year and an assistant coach this season. Bob Bland, head junior varsity coach, is a 1974 Cornell engineering graduate (head coach Jack Writer claims no such distinction).

In the action shot, Rice (9) works against Hartwick College players in the 1977 New York State NCAA championship game. Number 15 is Bettger.

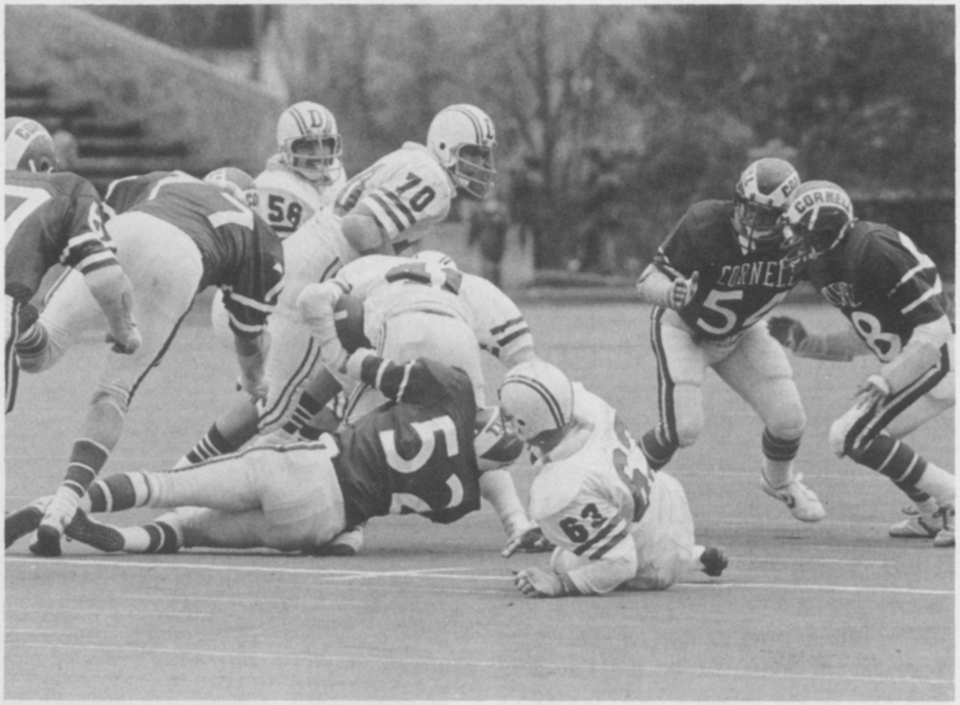
Capener

Rice

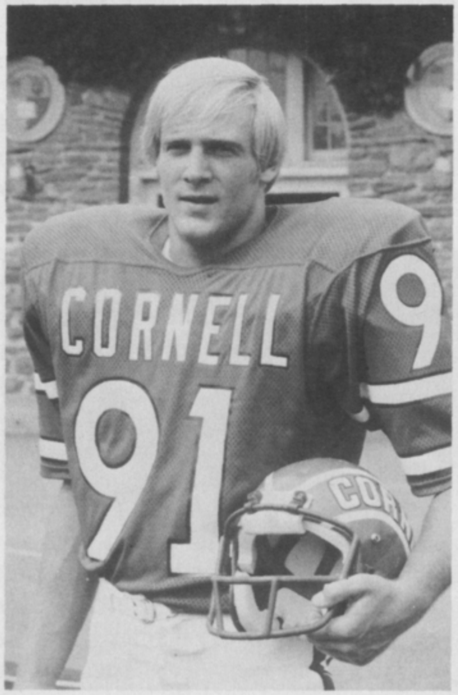
■ *The 1978 Big Red varsity football team had engineering senior Dave Kintigh from Endwell, N.Y., as co-captain.*

Most of the engineers on the varsity squad are in the photograph with head coach Bob Blackman. Front row, left to right: Mark Chenevey, Keith Manz, Scott Foreman, Rob Linagen, Brian Buck. Back row, left to right: Mike Johnson, Randy Smith, Mark Turley (an "interloper" from the Arts College), Marshall Roman, Mike Staun, Mark Lyons, Jim DeStefano, Steve Loizeaux, Dave Kintigh.

Right: an action shot, taken during the Homecoming game against Dartmouth, shows several engineers in defensive play. Center linebacker Jim DeStefano (52), a sophomore from New Hartford, N.Y., is making the tackle. Fellow engineers in the action are Scott Foreman (77), a junior from Williamsville, N.Y., and Mike Staun (98), a sophomore from Cincinnati, Ohio.



Kintigh

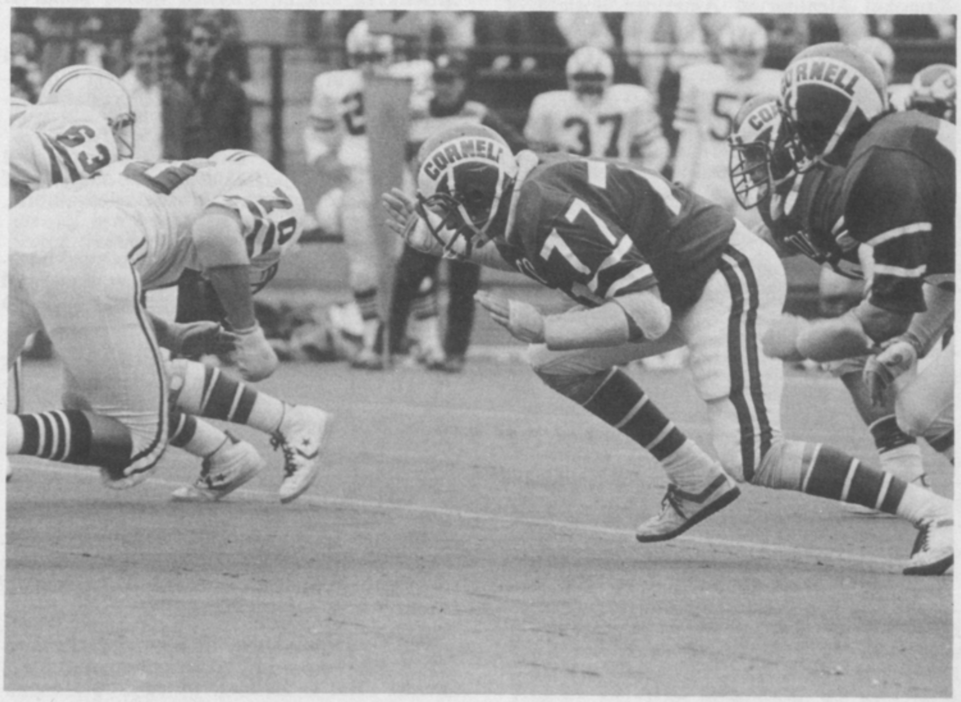


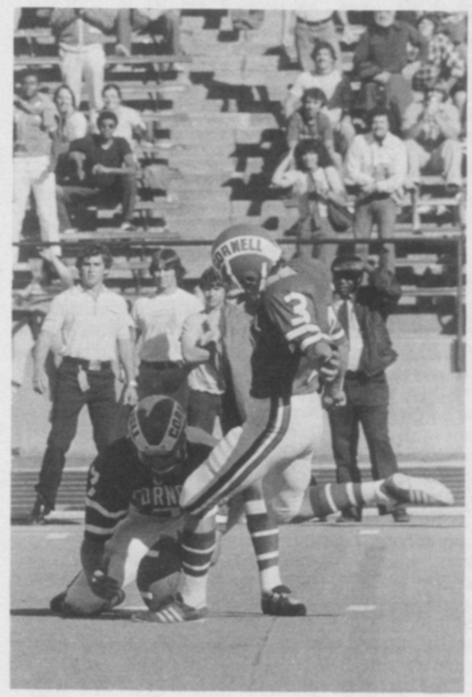
Other shots from the Dartmouth game show engineers in action.

Left: Mike Cobb, sophomore from Stamford, Conn., was a starting defensive back.

Left below: Scott Foreman (77) was a starter at defensive tackle.

Below: At this point in the season, Keith Manz, junior from Saratoga Springs, N.Y., had kicked three field goals and eleven straight extra points for the Big Red.





FACULTY PUBLICATIONS

The following publications and conference papers by faculty and staff members and graduate students of the Cornell University College of Engineering were published or presented during the period June through August 1978. Earlier entries inadvertently omitted from previous listings are included here in parentheses. The names of Cornell personnel are in italics.

■ AGRICULTURAL ENGINEERING

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Levine, G. 1978. Drought impacts, watershed management and climate. Moderator's discussion. In *Proceedings of conference on water conservation.* Ann Arbor, Michigan: Public Information Office, Great Lakes Basin Commission.

Martin, J. H.; Loehr, R. C.; and *Cummings, R. J.* 1978. *The oxidation ditch as a dairy cattle waste management alternative.* Ithaca, New York: Department of Agricultural Engineering, Cornell University.

Pellerin, R. A.; Millier, W. F.; Lakso, A. N.; Ruhkugler, G. E.; Throop, J. A.; and *Allport, T. E.* (1978). Apple harvesting with an inertial vs. impulse trunk shaker on open-center and central-leader trees—Part I. *Transactions of the ASAE* 21(3):407–413.

Rehkugler, G. E. 1978. Simulation of Articulated-Steer Four-Wheeled Drive Agricultural Tractor Motion and Overturn. Paper read at Summer Meeting of American Society of Agricultural Engineers, 27–30 June 1978, at Utah State University, Logan, Utah.

Robillard, P. D.; Hexem, R. W.; Walter, M. F.; and *Gilmour, R. B.* 1978. Farm Conservation Plans as a Water Quality Management Tool. Paper read at North Atlantic Regional Meeting of American Society of Agricultural Engineers, 6–9 August 1978, at University of Massachusetts, Amherst, Massachusetts.

Robillard, P. D.; Walter, M. F.; Hexem, R. W.; and *Gilmour, R. B.* (1978). Development of BMP's for Agriculture—New York State Strategy. Paper read at Cornell University Conference on Best Management Practices for Agriculture and Silviculture, 26–28 April 1978, in Rochester, New York.

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Walter, M. F.; Robillard, P. D.; and *Hexem, R. W.* 1978. BMP for Manure in New York State. Development of a "Best Management Practices" Strategy. Papers read at Summer Meeting of American Society of Agricultural Engineers, 27–30 June 1978, at Utah State University, Logan, Utah.

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Cohen, C., and Leal, L. G. 1978. Light scattering from spheroids in shear flows. I. The orientation correlation. *Journal of Chemical Physics* 68:5348–5356.

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▪ CIVIL AND ENVIRONMENTAL ENGINEERING

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Bialis, W. F., and *Loucks, D.P.* (1978). Nonstructural floodplain planning. *Water Resources Research* 14(1):67–74.

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