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The Moons of Uranus

Voyager 2 photographed the five major moons at close range. All have icy surfaces, but they are darker and rockier than Saturn's moons. Early in their history three were geologically vigorous

by Torrence V. Johnson, Robert Hamilton Brown and Laurence A. Soderblom

Picture this: You are an observer at Uranus, where you have been in orbit for millions of years. It has been an uneventful epoch. Nothing much changes in your gray world; everything froze long ago. Then, at a time like any other, you spot a point of light streaking toward you out of the sun. You investigate. What you find is almost comical: a small pile of metal, a dish with several awkward, randomly gyrating protuberances, the whole contraption hurtling along at a frantic pace. In what seems to you an instant the interlude is over, and you are alone again in the serene regularity established by the planet, its circular rings and its icy, cratered moons.

Now move to California, specifically to the Jet Propulsion Laboratory: You are one of us, one of the people who launched that metal contraption, called *Voyager 2,* on its mission. Even from our comparatively limited perspective (Uranus was discovered by William Herschel only two centuries ago), the *Voyager* flyby on January 24, 1986, seemed brief. That was particularly true for those of us interested in the planet's five major satellites, which are barely visible from the earth even through large telescopes. When *Voyager 2* shot by Uranus at 72,000 kilometers per hour, we had less than a day to collect essentially all the detailed information we have ever had on the moons—and possibly ever will have: at present no further missions to Uranus are planned.

The technical obstacles were formidable. Originally intended to operate only as far as Saturn, where sunlight is four times as intense and where the moons are on the average about twice as reflective, *Voyager 2* had to contend at Uranus with targets much dimmer than those for which its cameras had been designed. To gather enough light for an image the camera shutters had to be left open for several seconds. Unless some way could be found to correct for the motions of the spacecraft and of the moons themselves, the pictures would be smeared to near uselessness. Imagine trying to photograph a speeding, charcoal-gray race car on an overcast day with very slow film and you will get an idea of the challenge that confronted *Voyager 2* and its handlers.

The challenge was fully met. While the spacecraft was proceeding from Saturn to Uranus engineers at the J.P.L. devised a method of compensating for its complex motions [see "Engineering *Voyager 2*'s Encounter with Uranus," by Richard P. Laeser, William I. McLaughlin and Donna M. Wolff; SCIENTIFIC AMERICAN, November, 1986]. The fruits of their efforts were high-quality, unsmeared images of all five major Uranian satellites: Oberon, Titania, Umbriel, Ariel and Miranda. In the case of Miranda, the innermost of the five, the images had a higher resolution than any made by *Voyager 1* and *Voyager 2* at Jupiter and Saturn. Given these results, *Voyager 2* does not appear comical or awkward to us; as a scientific experiment, it looks downright elegant.

The brevity of the Uranus encounter arose not only from the speed of the spacecraft but also from the unusual geometry of the Uranian system, which is tipped on its side. At present the planet's south pole is pointing toward the sun and the earth. Since the moons orbit roughly in the equatorial plane, *Voyager 2*'s path through the system resembled that of a bullet piercing a bull's-eye target. Instead of passing close to individual moons sequentially, as it did at Jupiter and Saturn, the probe made its closest approach to all the Uranian moons at about the same time. To ensure that each moon received high-resolution photographic coverage, the imaging sequence had to be planned to the second. Even with careful planning, though, no more than half of each moon could be photographed, because currently only the southern hemispheres are sunlit.

In the months before the closest approach a lot of camera time was devoted to scanning the planet's equatorial plane for new satellites. There was good reason to suspect their existence: Jupiter has 16 moons and Saturn 17, most of them tiny objects not visible from the earth. *Voyager 2* found 10 new satellites at Uranus, bringing that planet's total to 15. Two of the new moons are gravitational "shepherds" that patrol the inner and outer edges of the planet's largest, outermost ring. The other eight follow circular orbits between the rings and Miranda. All but one of the new satellites have diameters between 40 and 80 kilometers. The exception, designated 1985U1 pending the assignment of an official name by the International Astronomical Union, is 160 kilometers across.

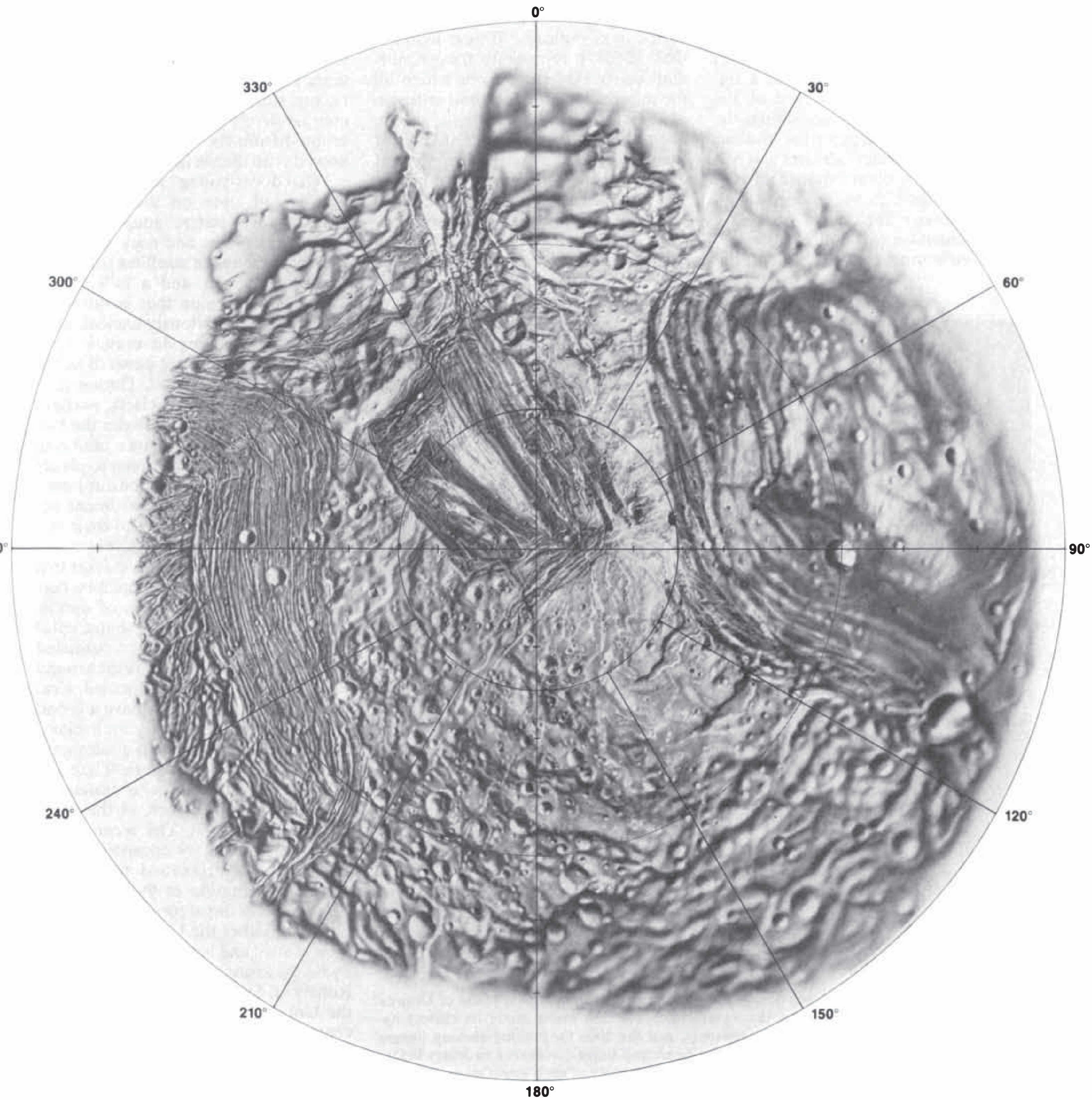
Because 1985U1 was detected more than a month before the encounter and because it happened to be on the same side of the planet as Miranda, we and

MAP OF MIRANDA based on *Voyager 2* images is a stereographic projection of the moon's southern hemisphere; the south pole is at the center and the equator is the outer ring. Only the southern hemispheres of the Uranian moons were photographed because only they are sunlit. Miranda is the smallest and most exotic of the five major moons. Superposed on its ancient cratered plains are three younger, less cratered regions of grooved and ridged terrain known as the "ovoids." The moon's surface is also crisscrossed by fracture zones; the one at the top of the map includes a cliff that is between 10 and 20 kilometers high. The Miranda map and the other maps in this article were prepared by workers at the U.S. Geological Survey in Flagstaff under the direction of R. M. Batson.

our colleagues were able to trade in a camera-time slot originally allocated to Miranda and make a closeup picture of the new moon. The image shows a somewhat irregular object with a dark, cratered surface that reflects only 7 percent of the incident sunlight. The other new satellites were not observed at close range, but they appear to be equally dark, as do the particles that make up the rings.

In that respect they are far from distinctive. Actually most of the solid material in the outer solar system that is not bright ice is very dark, with an albedo, or reflectance, of about 10 percent or less. The nature of this dark material has been the subject of considerable debate in recent years. Most investigators agree that it is dark because it is rich in carbon, like soot. The most obvious explanation is that it is essentially the same stuff as is found in carbonaceous chondrites: primitive meteorites that come from the asteroid belt between Mars and Jupiter and consist of hydrated silicates, or clays, mixed with dark, carbon-rich organic substances. Such mixtures form only at relatively low temperatures. Theoretical models suggest that conditions in the early solar nebula would have been appropriate for the formation of carbonaceous rocks from the asteroid belt outward.

Alternatively, the carbonaceous material might not be primordial rock; it might have been produced more recently, by the irradiation of methane ice or methane-contaminated water ice, which are also predicted to be present in the outer solar system. Laboratory studies have shown that ultraviolet light or energetic electrons (such as those in the solar wind or in plan-



etary magnetospheres) can induce reactions in which the methane forms a dark residue of complex organic compounds. This mechanism has been variously invoked to explain the production of dark interstellar grains, the low reflectance of cometary nuclei and the peculiar dark side of Saturn's moon Iapetus. Indeed, some workers think it accounts for the organic material in carbonaceous rocks. If they are right, then the question about the darkening of methane in the outer solar system is not so much whether it has occurred, but when: whether it was important only four and a half billion years ago, when the carbonaceous rocks formed, or whether it also occurred later on the surface of satellites.

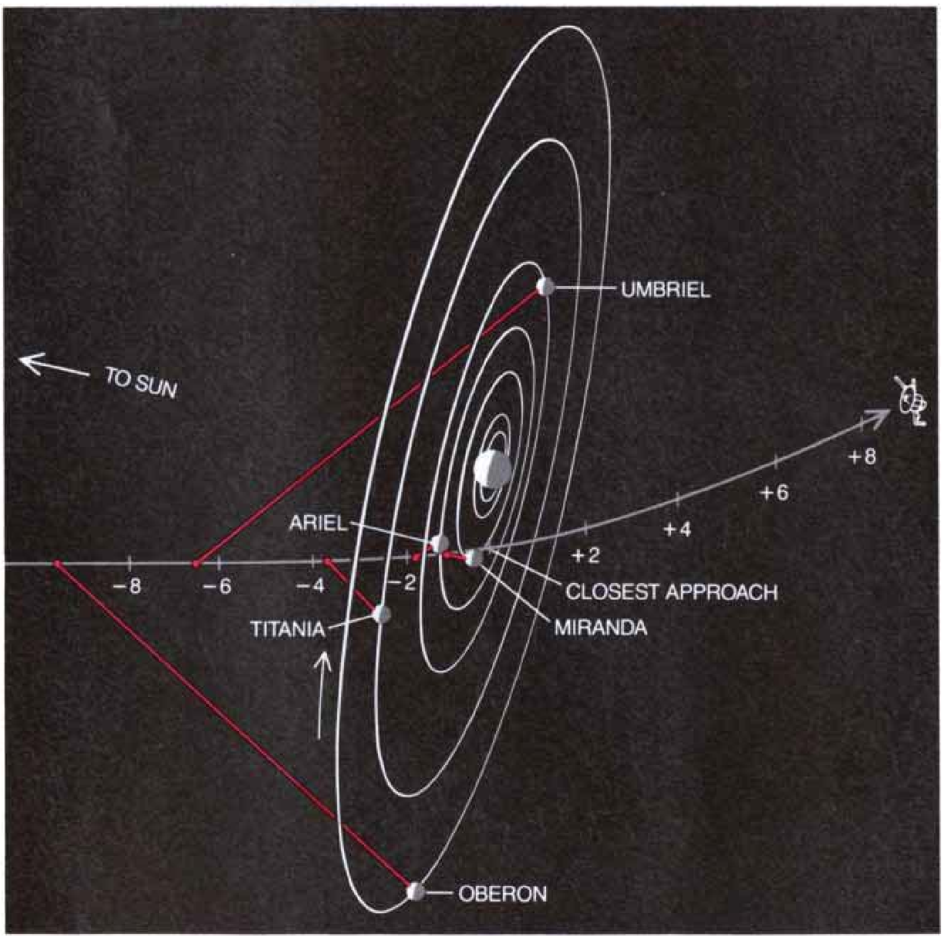
So far there is no compelling reason to believe the process has had a significant effect on the surface of the Uranian satellites. For one thing, the presence of methane on the moons, unlike that of water ice, has not yet been verified by observations from the earth. (*Voyager 2* is not equipped with a spectrometer capable of analyzing the composition of satellite surfaces.) In our view most of the dark material in the Uranian system is probably primordial carbonaceous rock, although darkened methane may have been added to the original mixture in a few locations. Experiments done by Roger N. Clark, then at the University of Hawaii at Manoa, indicate that small quantities of carbonaceous rock (less than 1 percent by volume), when they are mixed thoroughly with water ice, are enough to darken the bright ice, yielding a reflectance as low as the 7 percent level exhibited by 1985U1.

The five major Uranian moons are not nearly as dark as 1985U1; their albedos range from 20 percent (Umbriel) to 40 percent (Ariel). The observation is significant. If one assumes that 1985U1 represents the primordial ice-rock mixture from which all the moons were formed, one must explain why the larger moons should be brighter. The answer is that 1985U1 is probably a homogeneous mixture of ice and rock, whereas the major moons are not. Instead they have undergone varying degrees of differentiation: some of the dense rock has settled toward the center of the moon and some of the lighter, brighter ice has risen to the surface. The differentiation process requires internal heat, and the heat sources in all the Uranian moons probably dwindled to insignificance long ago. But judging from the *Voyager* pictures, all five moons—notably Ariel and Miranda—seem to have been geologically active early in their history.

Evidence of geologic activity on an icy satellite can take several forms. If extensive differentiation has taken place, one may see large patterns of bright and dark markings on the surface corresponding to regions where either less rock or more rock is mixed with ice. If the moon's crust has been disrupted by tectonic movements, it should have visible fault lines. And if its internal heat source has been intense enough to drive volcanic activity, one should see regions covered by comparatively young material that has erupted from the moon's interior and flowed onto the surface.

What does "young" mean? The only markers of time on the surface of satellites are craters gouged out by the chunks of ice and rock that have rained down on the satellites since they first formed four and a half billion years ago. A region that is saturated with craters is obviously ancient; a region totally lacking in craters must have had its surface re-covered in the geologically recent past. Dating geologic features more precisely, particularly if their ages fall between the two extremes, is tricky, because cratering rates have varied from planet to planet and have not remained constant over time. The heaviest bombardment occurred while the planets and their satellites were still accreting debris.

During this early period at least two distinct populations of impactors, corresponding to two sources of debris, struck the satellites of the outer solar system. The first population consisted of material remaining in orbit around the sun after the planets formed. Craters from this population have a broad size distribution; typically their diameters range from less than a kilometer to hundreds of kilometers. They are found throughout the solar system on the oldest terrains, such as the highlands of our moon. The second population of impactors consisted of debris left in orbit around the planets after the formation of their satellites. Most of these impactors were relatively small. Before the Uranus encounter their craters had been detected primarily on the moons of Saturn, notably by Robert G. Strom and his colleagues at the University of Arizona. The heliocentric and planetocentric bombardments overlapped, but the planetocentric bombardment seems to have end-



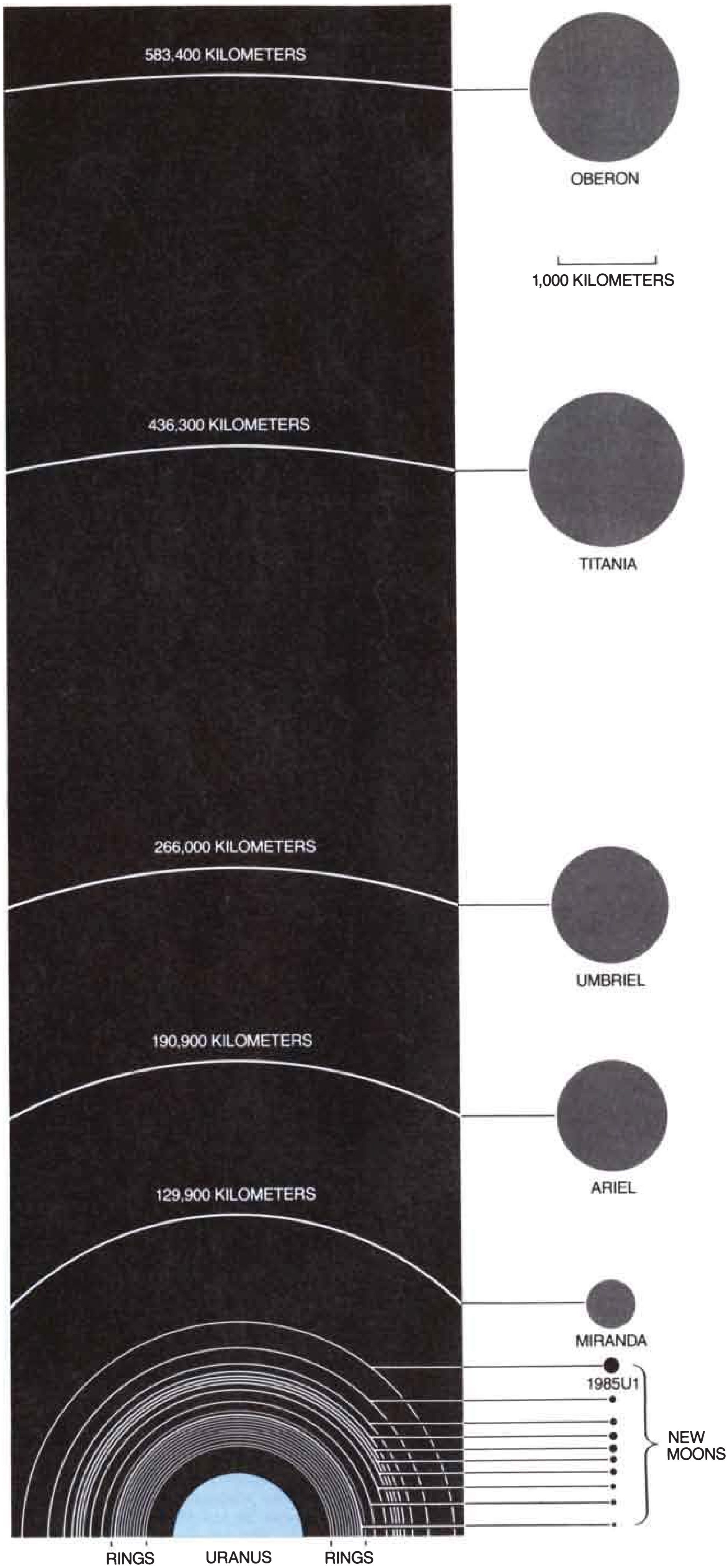
TRAJECTORY of *Voyager 2* **was nearly perpendicular to the equatorial plane of Uranus. Since the moons orbit roughly in the equatorial plane, the probe made its closest approach to all the moons almost simultaneously, and the time for making closeup images was short. The colored lines indicate the positions and times (measured in hours before the closest approach to the planet) at which the best images of each moon were obtained.**

ed somewhat later. This fact is a helpful clue to the early history of the Uranian moons.

Oberon and Titania, the outermost and largest of the moons, are both about 1,600 kilometers in diameter (less than half the size of the earth's moon), and they have roughly the same mass. Their surfaces, which are rich in water ice, reflect between 25 and 30 percent of the incident sunlight and are a fairly uniform gray. The gray is interrupted only by bright rays around a few craters; neither satellite displays global patterns of bright and dark markings. In spite of these similarities the two moons clearly evolved differently.

Oberon has a few features that look a bit like faults, but it shows little evidence of major tectonic disruption. Its surface is nearly saturated with large, old craters, which range in size from the limit of resolution of the images (about 12 kilometers) to more than 100 kilometers. The fact that the large craters have not been obliterated indicates that Oberon's surface has not been re-covered by fresh material since the heliocentric bombardment ended some four billion years ago.

That does not mean the satellite was completely inactive. The floor of a few of the largest craters is covered with patches of very dark material similar to that seen on 1985U1. The appearance of the craters is reminiscent of craters with dark floors, such as Tsiolkovsky, in the highlands of the earth's



URANIAN SYSTEM includes at least 11 rings and 15 moons. The orbits are measured from the center of Uranus, which has a radius of 25,600 kilometers; the moons are drawn to a common scale. The five major moons were known before the *Voyager* flyby. Of the 10 small moons discovered by *Voyager 2*, only the largest, 1985U1, was photographed at close range (*above*). Its surface is darker than that of the major moons. The large crater on its right limb is approximately 40 kilometers in diameter.

moon. On the moon the dark deposits are thought to have been laid down by volcanic eruptions following the enormous impacts that dug out the craters. Oberon too may have seen some early, localized volcanic activity. Its dark patches may consist of a mixture of ice and carbonaceous rock erupted from the interior. Alternatively, the volcanic flows could have included methane-containing ice that was darkened after it reached the surface.

Whereas Oberon has been largely a passive target for incoming projectiles, Titania has not. Its surface bears dramatic evidence of global tectonics: a complex set of grabens, or rift valleys, bounded by extensional faults. Furthermore, although Titania's surface is heavily cratered, the evidence suggests that the craters were formed by impactors from the second, planetocentric population. Titania must have endured at least as intense a bombardment from heliocentric impactors as Oberon, and yet it has only a few large craters attributable to that population. Evidently most of the large craters were erased by some resurfacing process. Moreover, since the crater density is not uniform—there are several plains that are distinctly smoother and less cratered than the rest of the surface—the resurfacing must have lasted for a considerable time.

According to one model of Titania's evolution, the resurfacing took the form of extensive volcanic extrusion of material onto the surface. The volcanism began while the heliocentric bombardment was under way. Large craters disappeared because they were flooded or simply because the icy crust around them, which would still have been relatively warm and soft, collapsed. As the moon radiated away its internal heat, it began to freeze from the outside in. Eventually all the liquid, primarily water, froze in the interior. The water did what water always does when it freezes under low pressure: it expanded, and because there was so much of it, the entire surface of the moon was stretched. The crust ruptured along a network of extensional faults, and blocks of crust dropped down along the faults, forming the enormous grabens. The tectonic motions may have been accompanied by further extrusions of fluids; these late extrusions could have produced the smooth plains.

By the time most of the current surface had been emplaced the first bombardment had ended, and only smaller, planetocentric impactors continued to rain down on Titania. Finally, when the space around Uranus had been swept clean of debris, that bombardment also stopped. For the past three billion years or so Titania has been a quiet body, disturbed only by the impact of an occasional comet.

Eugene M. Shoemaker of the U.S. Geological Survey, an expert on cratering rates, has proposed a more drastic type of resurfacing. He thinks the early cratering of Titania by heliocentric objects was so intense that a large, late-arriving impactor could have blasted the moon apart. The shattered pieces would have remained confined to Titania's orbit and relatively soon would have reassembled into a moon. The reassembled moon would have had a new surface, one that bore no trace of the early bombardment. One virtue of Shoemaker's hypothesis is that it can explain why Oberon and Titania have similar bulk properties and yet look so different: because it is closer to Uranus, whose gravitational field must have focused and accelerated incoming debris, Titania was more likely to be shattered.

Umbriel and Ariel, the next two Uranian moons, are another interesting pair. They have nearly the same diameter (1,190 kilometers and

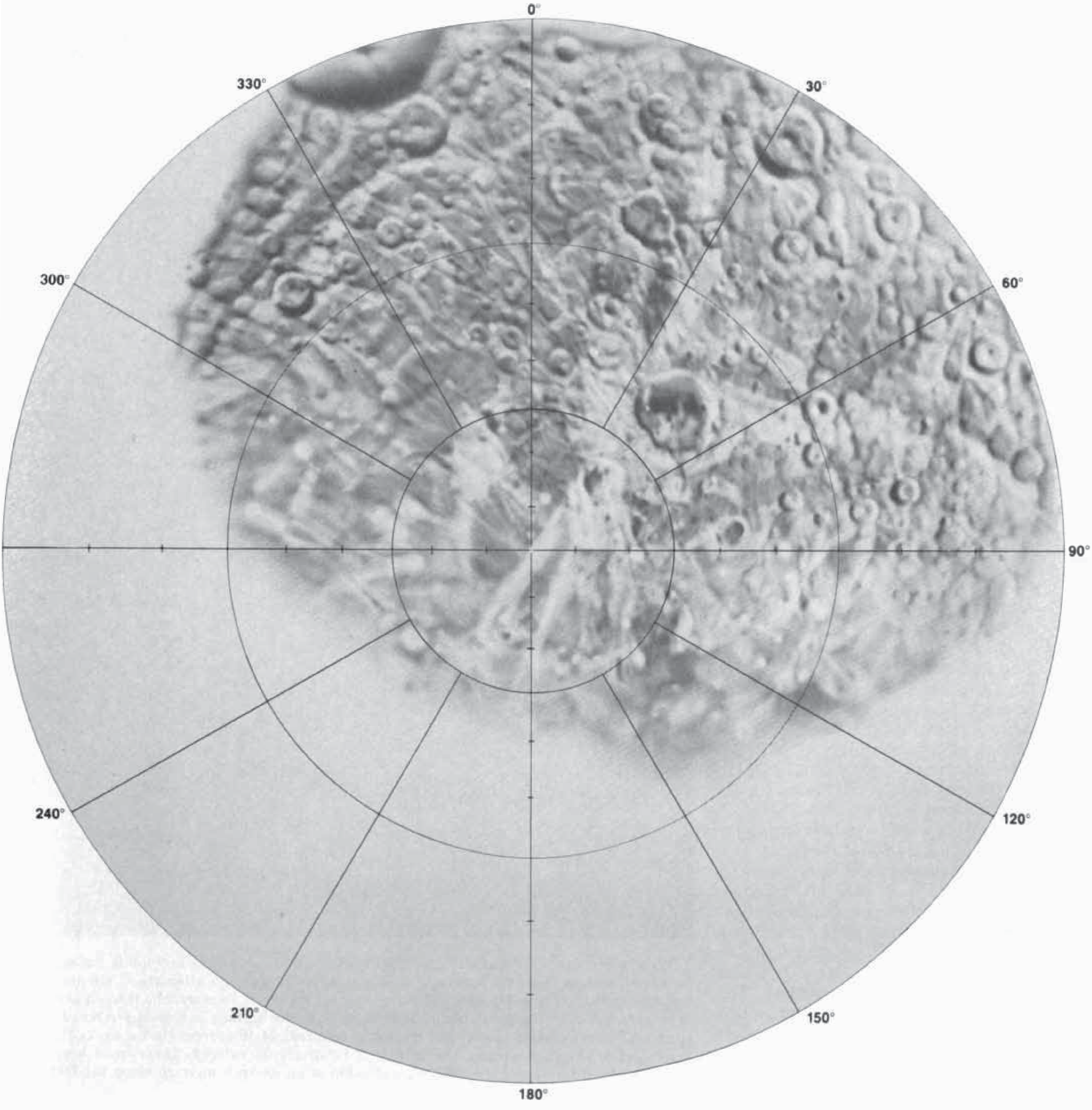
OBERON was photographed by *Voyager 2* from a distance of 660,000 kilometers. It is only slightly smaller than Titania, the largest of the Uranian moons, but its ancient, densely cratered surface shows few signs of geologic activity. Dark deposits that may be volcanic in origin are visible on the floor of a few craters, notably the large one near the center of the photograph; on the map of Oberon's southern hemisphere (*right*) that crater lies between 30 and 60 degrees longitude at a latitude of about 50 degrees. The crater is more than 100 kilometers across, and like the many other large craters on Oberon it dates from the bombardment by heliocentric debris that ended four billion years ago.

1,160 kilometers respectively) and the same mass, but the contrast between them is even stronger than the contrast between Oberon and Titania.

Umbriel is remarkable for its almost total blandness. Like Oberon and Titania it lacks global-scale variations in brightness, but unlike those two bodies its surface is not marked by bright ray craters. (Bright rays are thought to form around craters on icy satellites because the impacts eject clean, buried ice out onto the surface.) As *Voyager 2* neared the Uranian system it appeared that Umbriel might lack craters altogether, which would imply its surface was being regenerated even today. The high-resolution images made at the closest approach, however, revealed a surface dominated by large craters from the first bombardment; only the rays are absent.

Explaining Umbriel's blandness is surprisingly hard. Conceivably bright rays around its craters could have been erased by micrometeoroids that peppered the surface and mixed the ray material with the underlying dark material. (The process is called impact gardening.) A second possibility is that the rays contained methane that has been darkened by energetic radiation. Both hypotheses fail to explain why bright rays are absent on Umbriel but not on the other Uranian moons.

Perhaps the most straightforward explanation is that bright rays never formed on Umbriel. If Umbriel were covered by a blanket of dark material several kilometers thick, the ejecta from an impact would be dark; such dark-ray craters have been observed, for example, on Jupiter's moon Ganymede. The blanket might consist of a uniform, primordial mixture of



ice and rock. A primordial blanket on Umbriel is at least plausible, because Umbriel is smaller than Oberon or Titania and so might be expected to have undergone less differentiation. In addition the fact that it has the lowest reflectance (20 percent) of the Uranian moons supports the notion that it has a high concentration of dark, carbon-rich material near its surface.

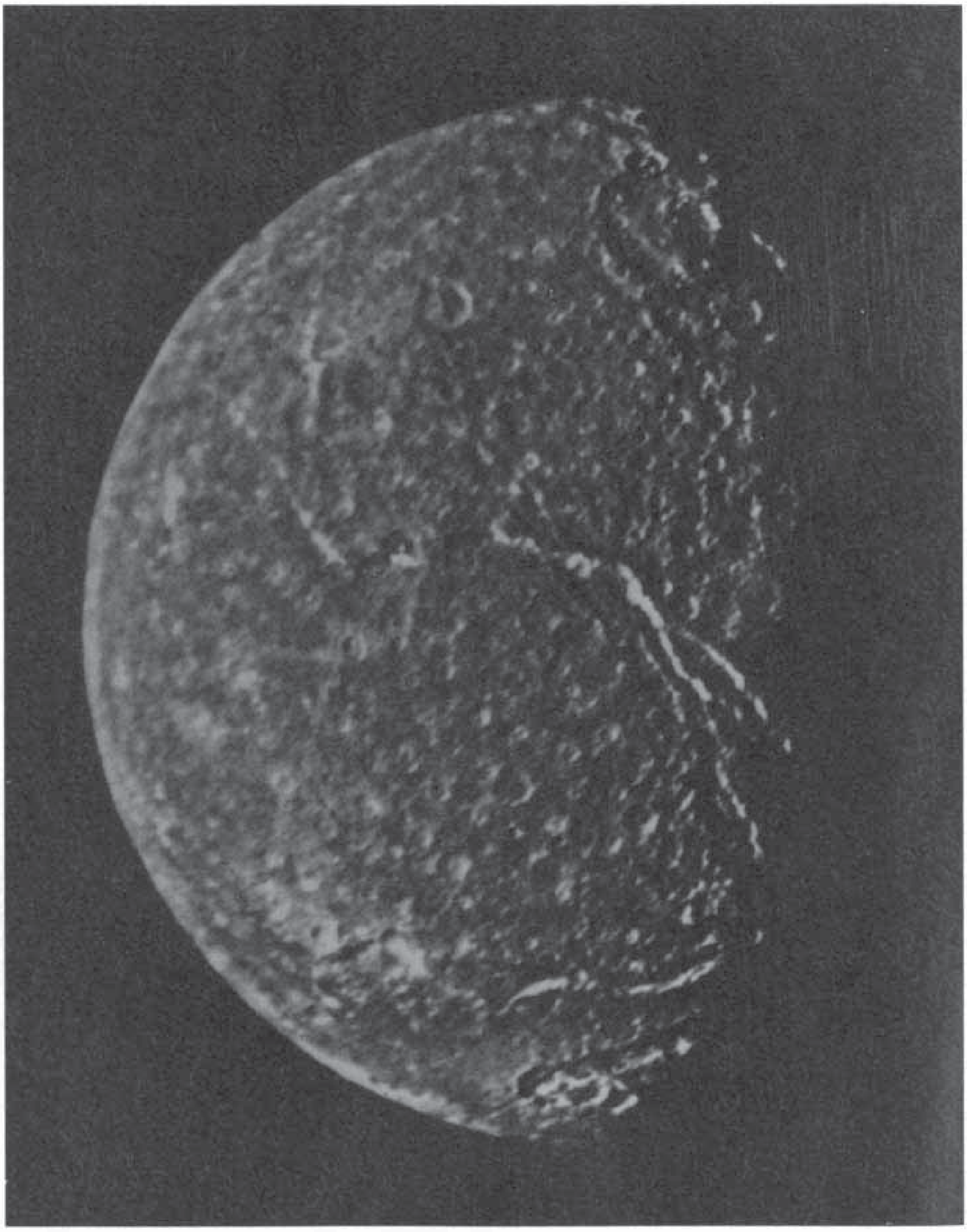
Nevertheless, there are problems with this hypothesis as well. Although most of Umbriel is bland, the moon is not altogether featureless. On the contrary, it has two rather striking bright features near the equator: a ring 80 kilometers in diameter that appears to cover the floor of an impact crater, and a spot on the central peak of another large crater. The origin of these features is a mystery, but the bright material must have come from below the surface. This means that the dark blanket, if it exists, would have to be thin or absent in those two locations and only there.

Whereas Umbriel is the darkest of the major Uranian moons, Ariel is the brightest; it has a reflectance of roughly 40 percent. And whereas Umbriel's surface is among the oldest, most cratered surfaces in the Uranian system, Ariel's is one of the youngest and least cratered. Ariel's history is reminiscent of Titania's, except that the geologic activity on Ariel was more intense, more extensive and more prolonged. Like Titania, Ariel has almost no craters from the heliocentric bombardment. In addition it has only about a third as many craters from the planetocentric bombardment as Titania, indicating that its surface was remade over a broader area and a longer period. Its global network of extensional faults is also more fully developed; in some places on Ariel the fault valleys are tens of kilometers deep.

The resurfacing of Ariel was a volcanic process. The evidence for extrusion of material onto the surface is much more conclusive than in the case of Titania. The floors of the fault valleys in the hemisphere that is always pointed toward Uranus (the Uranian moons, like the earth's moon, are locked in synchronous orbits) are covered with a smooth, relatively uncratered unit. Because the smooth unit covers previously existing geologic features—the most dramatic example is a large, half-buried crater—it must have been emplaced by volcanic flows.

In some areas the smooth unit displays grooves and ridges that parallel the axes of the fault valleys. The pattern suggests that material welled up through fractures along the axes and spread out over the valley floors, somewhat in the manner of lava erupting from rifts on the floor of the earth's oceans. The upwelling material on Ariel was almost certainly not molten rock. Instead it was probably a relatively warm, plastic mixture of ice and rock that flowed much as a terrestrial glacier does. The mixture must have been fairly viscous: in places where it has buried older features its edges form a steep scarp that is about a kilometer high.

Although Ariel has been a surprisingly active little moon, in some ways its style of activity—crustal rifting and icy volcanic flows—is reassuringly familiar, similar to what was seen on Jupiter's Europa and Ganymede and on Saturn's Enceladus. Miranda, on the other hand, is one of the strangest worlds yet observed. The innermost (and with a diameter of about 500 kilometers the smallest) of the major Uranian moons, it has barely enough gravitational strength to pull itself into a sphere. Yet its surface is a hodgepodge of complex and exotic geologic terrains that would seem more appropriate on a planet 10 times its size.

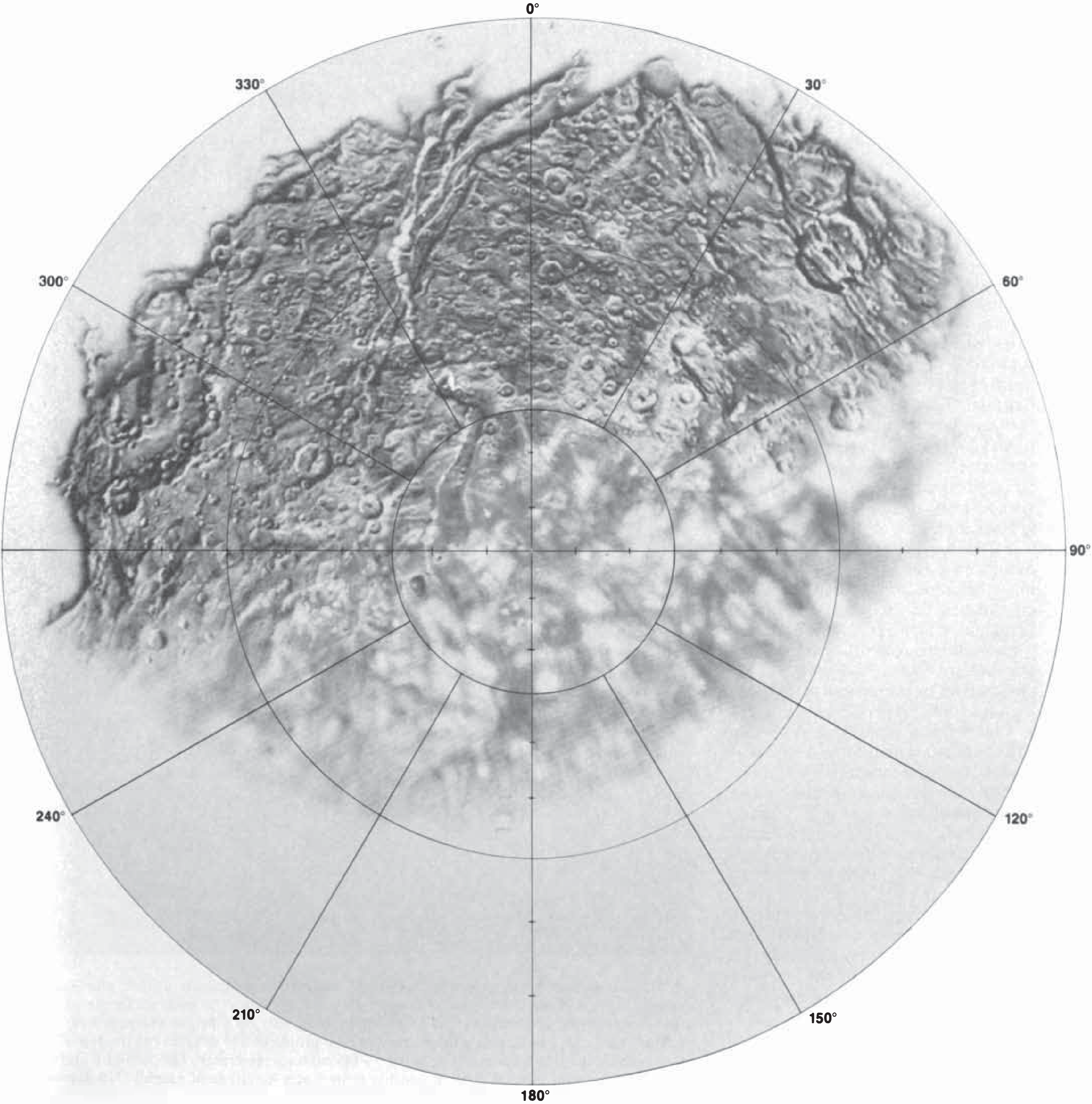


TITANIA was much more active geologically than Oberon. The photograph is a composite of two images made by *Voyager 2* from a distance of 369,000 kilometers. Titania has fewer large craters than Oberon, indicating that its surface is younger, and it has a prominent network of extensional faults, indicating that the surface has been stretched. In some areas, for example near the equator at a longitude of 30 degrees (in the lower right-hand part of the photograph), the surface is relatively uncratered. These smooth areas may have been formed by the volcanic extrusion of an ice-rock mixture along the faults.

The oldest geologic unit on Miranda consists of densely cratered rolling plains pocked by the planetocentric bombardment. They cover most of the surface visible in the *Voyager* images, and they do not look particularly unusual. Superposed on the rolling plains, however, are three enormous, oval-to-trapezoidal regions that for lack of a better word we call the ovoids. The ovoids are between 200 and 300 kilometers in diameter, and judging from the number of craters on them they are substantially younger than the plains. They consist of locally parallel belts of ridges, grooves and scarps that abut one another at odd angles. Bright material as well as dark material is exposed along the scarps and in fresh craters inside the ovoids; in contrast, the rolling plains have a fairly uniform reflectance. Finally, both the ovoids and the plains are cut by huge fracture zones that circle Miranda, creating fault valleys whose steep, terraced cliffs are as much as 10 to 20 kilometers high.

The material in the ovoids may well be less dense than that in the plains. The bright areas along the scarps may consist of clean ice from below the surface, and the dark material is probably similar to whatever welled up in Oberon's craters. There is some evidence on Miranda for eruptive flows, although it is much less pervasive than on Ariel. In one of the ovoids material seems to have flowed out of a low, horseshoe-shaped cone, burying scarps and ridges and piling up behind a steep, lobe-shaped flow front.

The two models that have emerged to explain Miranda's strangeness both assume, for different reasons, that the ovoids are less dense than the roll-



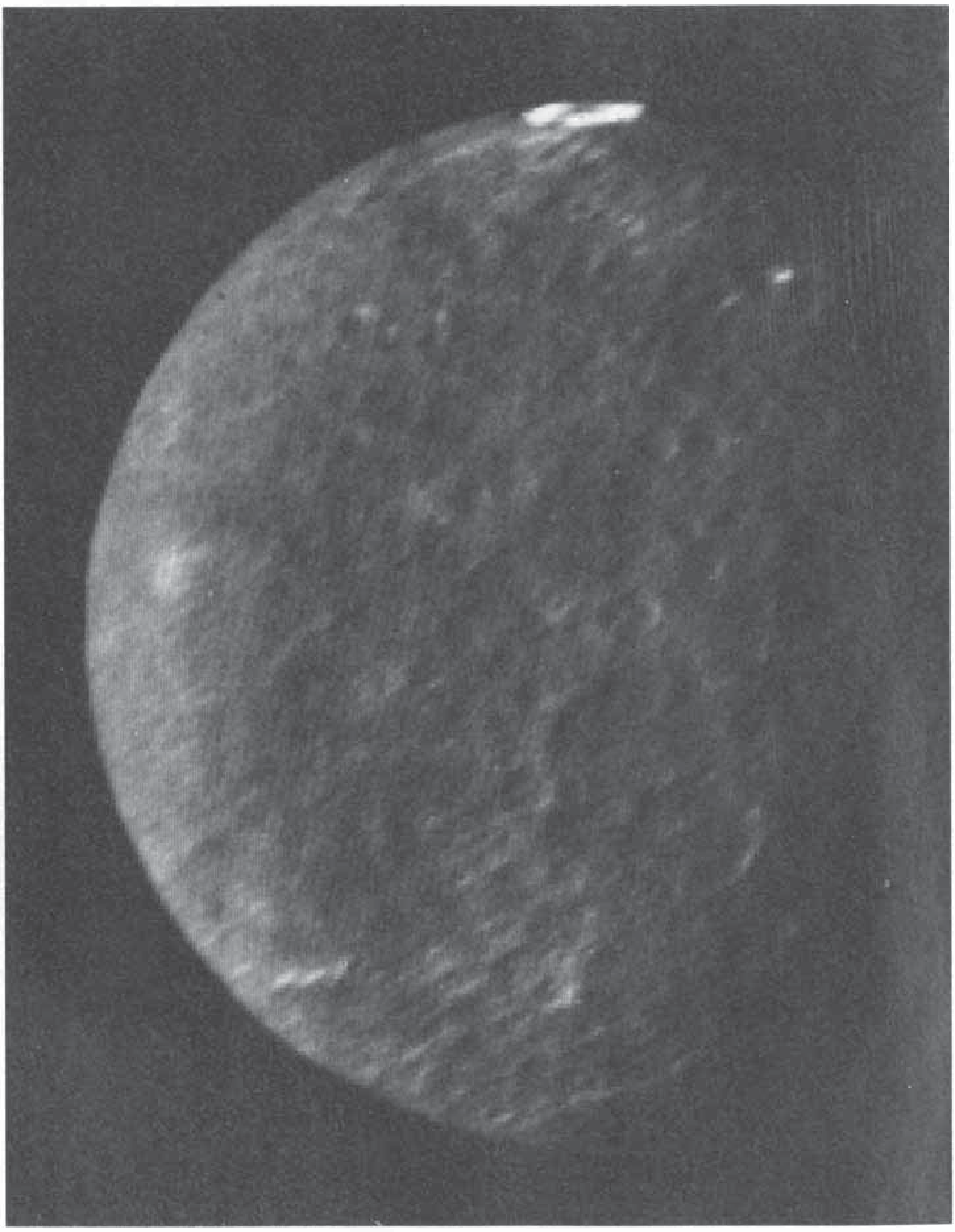
ing plains. The first model is based on Shoemaker's ideas about early cratering rates. Shoemaker thinks Miranda was blasted apart as Titania was, but five or more times rather than just once. Each time it reassembled itself. Before the last cataclysm, according to the theory, the rock and ice in the moon had time to become partially separated. Hence when Miranda was shattered again, it broke into large pieces, each of which consisted primarily of either rock or ice. When the pieces drifted randomly back together, large chunks of rock, which had been near the core of the old Miranda, became embedded in the surface of the new conglomerate. The new moon retained enough internal heat to allow viscous flow in its interior. As a result the rock masses began sinking toward the center again, enabling lighter ice to rise and flow into the space behind them and causing the surface to crack along concentric stress lines. The ovoids, in this view, are surface disturbances left by the sinking rock masses.

One argument against the theory is that it is hard to see how such large chunks of rock could remain intact through the total disruption and reaccretion of the moon. The cataclysm seems more likely to have yielded small pieces. An alternative view, put forward by one of us (Soderblom), holds that when Miranda accreted for the final time (whether it was actually blasted apart or not is unimportant), it was a fairly uniform mixture of rock and ice. Then, driven by its internal heat, it began to differentiate. As the rock sank toward the center, agglomerates of ice began rising toward the surface. In this scenario the ovoids were formed not by large sinking masses of rock but by large rising masses of ice, which eventually breached the surface. The pattern of the ovoids (they are all about the same size and are regularly spaced) suggests an internal organization to the flow, perhaps some form of convection cell.

The process of differentiation on Miranda was apparently never completed. If differentiation had continued, the ovoids would probably have been smoothed over, and Miranda would have been left with a mantle of solid ice surrounding a core of solid rock. Instead the moon was frozen at an embryonic stage of geologic development. Although some workers think the ovoids may be only a billion years old, it seems to us more likely that Miranda's evolution stopped between three and four billion years ago.

The striking thing about moons such as Ariel and Miranda is not that their geologic activity stopped long ago but that it ever began in the first place. Such a degree of activity in such small objects—Ariel is about one-third and Miranda less than one-sixth the size of the earth's moon—would have seemed extraordinary a decade ago. Then the primary source of internal heat in a solid planetary body was thought to be the gradual decay of long-lived radionuclides such as uranium, potassium and thorium. Because the quantity of radioactive elements in a planetary body is proportional to its volume, whereas the rate at which it loses heat is proportional to its surface area, a large body retains internal heat much longer than a small one and therefore undergoes a more prolonged geologic development. The terrestrial planets conform to this pattern. The earth is the largest, and it has clearly been the most active geologically; Mars is intermediate in size and has had a low level of volcanic activity throughout its history; Mercury and the earth's moon are small and had only an early, abbreviated evolution.

The moons of the outer solar system do not follow the pattern. During the past 10 years Voyager observations

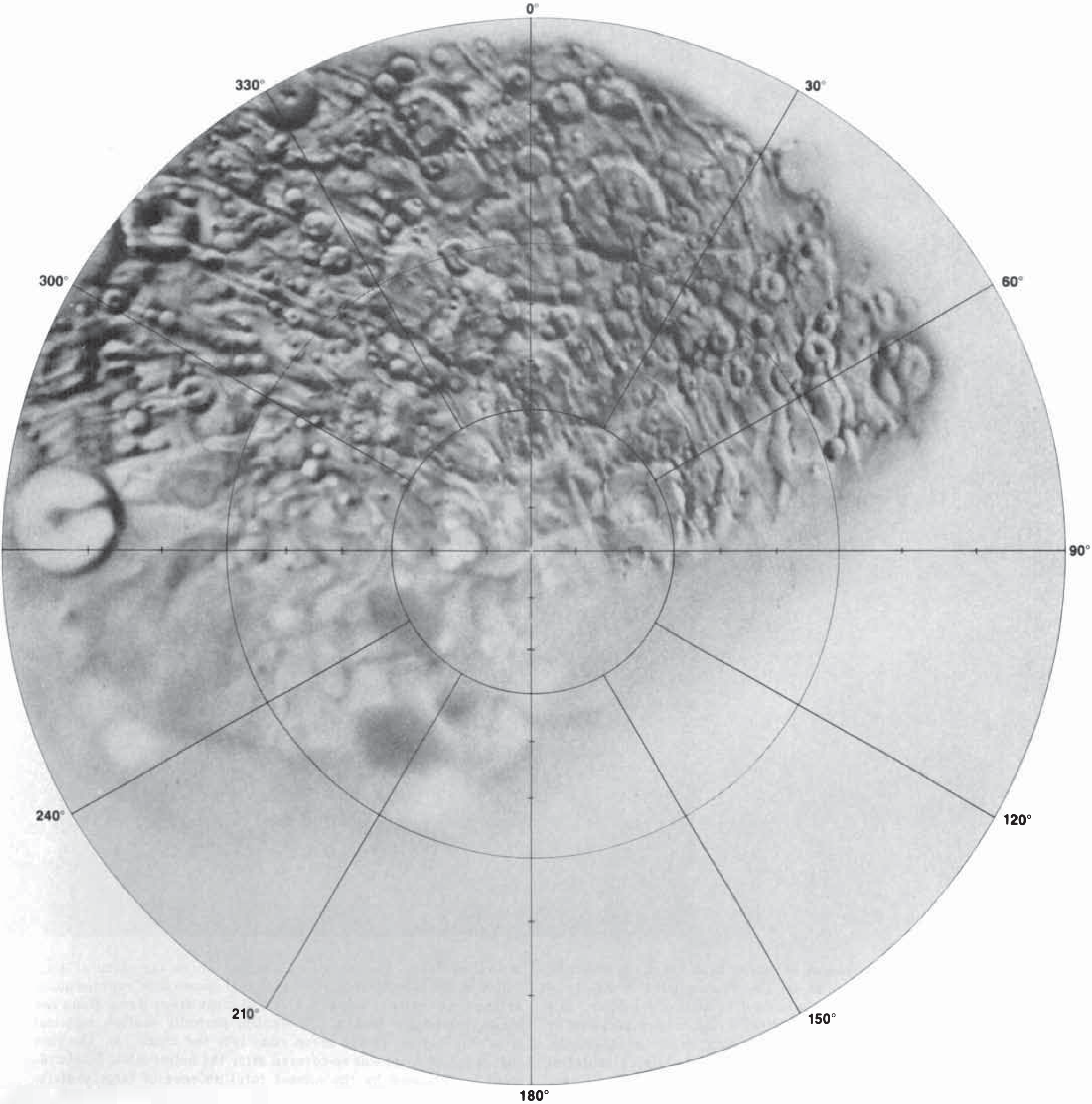


UMBRIEL is distinctive primarily for its blandness: its surface is a dark and nearly uniform gray, and the abundance of large craters shows that it is ancient. In the photograph made from a distance of 557,000 kilometers, only two bright features near the equator stand out. The first is a bright ring at a longitude of 270 degrees (at the top of the photograph); the ring appears to lie in an 80-kilometer-wide crater. The second feature is a bright spot on the central peak of another crater, at a longitude of roughly 310 degrees.

of more than 20 such moons have dramatically revised the conventional wisdom about the geologic history of small bodies. Jupiter's moon Io, where volcanoes are erupting even now, is only the most spectacular counterexample; a number of the other Jovian and Saturnian satellites also display evidence of significant geologic activity. To that list one must now add Miranda, Ariel and perhaps Titania.

The full implications of the Voyager observations have yet to be worked out, but a few guiding ideas have begun to emerge. The moons must have another energy source in addition to long-lived radionuclides. It may be that they received an early pulse of heating from short-lived isotopes such as iodine 129 or aluminum 26, both of which are thought to have been present in the primitive solar nebula. Another possible source of early heating is gravitational energy released by incoming debris as the moons accreted.

Tidal resonances are a third and potentially more prolonged source of heating. When the orbital periods of adjacent satellites differ by an integral factor, one satellite perturbs the other satellite's orbit at regular intervals that are multiples of the perturbed satellite's period. The effect is analogous to the one achieved by driving a pendulum at its resonance frequency: the perturbation is enhanced dramatically. As a result the perturbed moon's orbit becomes distinctly noncircular, or elliptical. Because of the ellipticity, the tidal bulge raised on the surface of the moon by the planet's gravity tends to shift up and down and back and forth. The shifting bulge can inject a huge amount of frictional energy into the moon, and that energy must

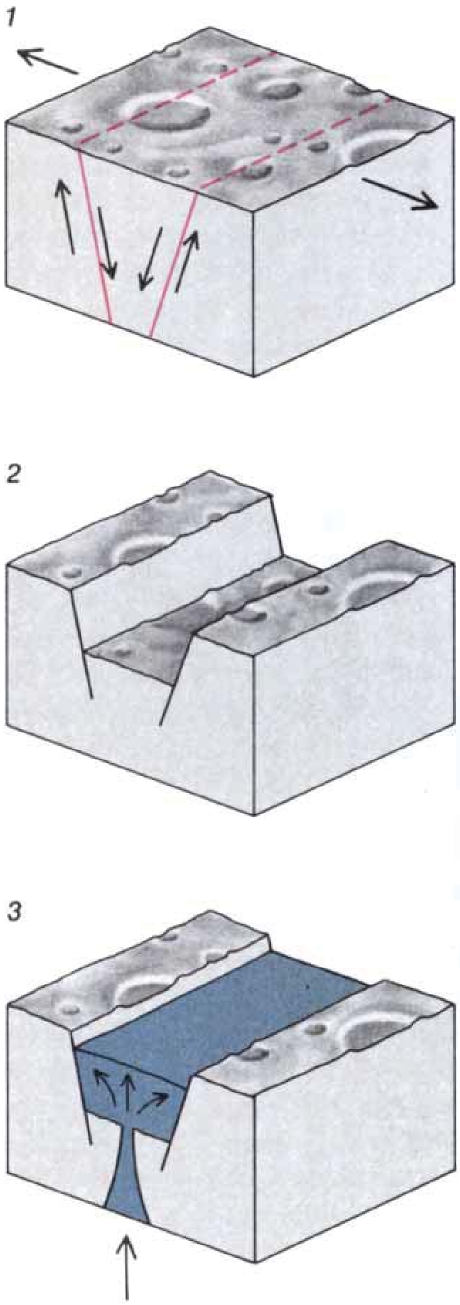


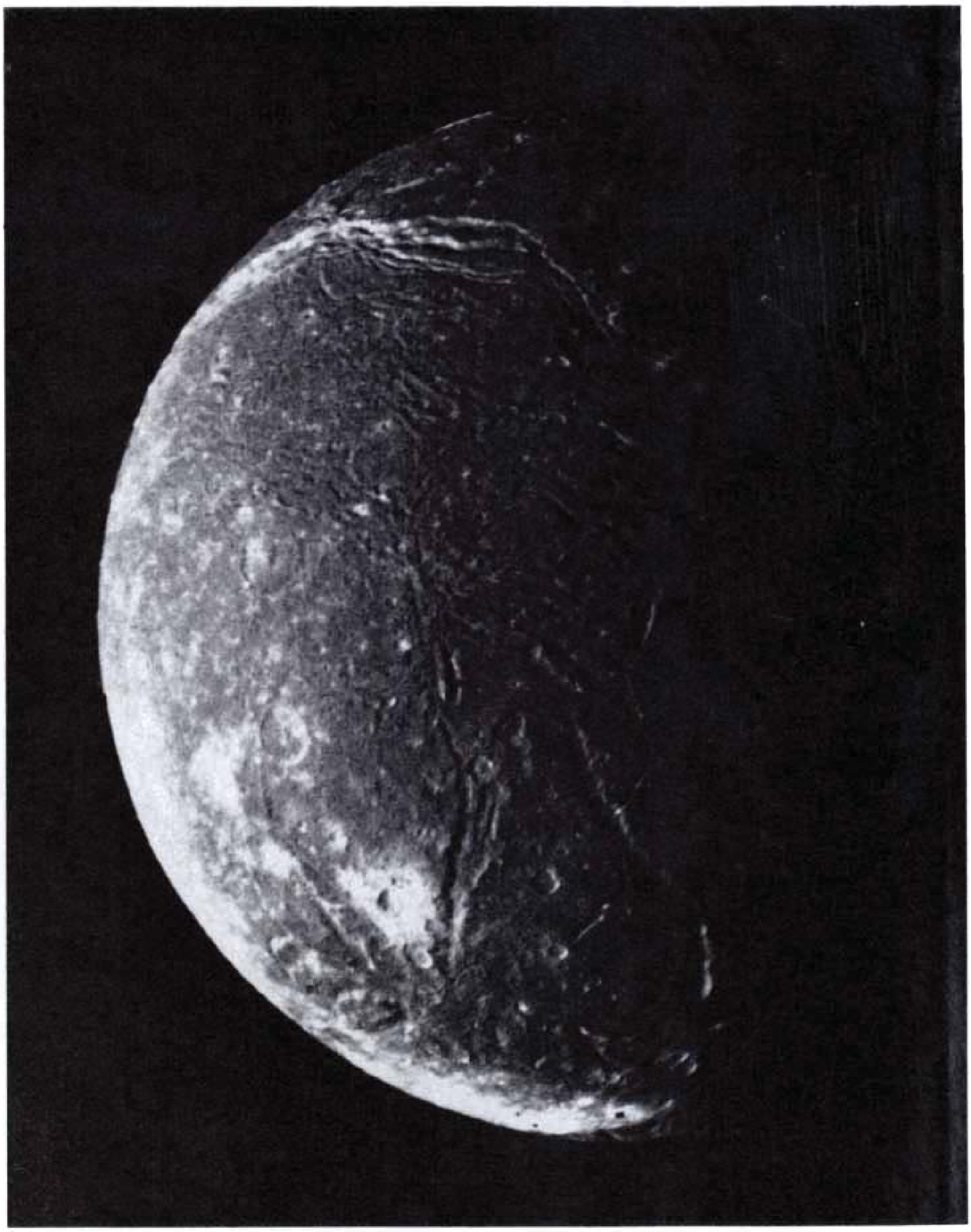
be dissipated as heat. Tidal heating is thought to account for geologic activity on Io, Europa and Enceladus.

The Uranian moons are not now in resonance. But as Steven W. Squyres, Ray T. Reynolds and Jack Lissauer of the National Aeronautics and Space Administration's Ames Research Center pointed out in a paper published before the *Voyager* flyby, Miranda, Ariel and Umbriel may have passed through a resonance in the geologically recent past. At present tidal heating seems the likeliest source of the strong geologic activity on Miranda and Ariel. The tidal effect on Umbriel would have been less significant because it lies farther from Uranus; that would explain why Umbriel and Ariel developed so differently even though they are about the same size.

The unexpected activity of moons in the outer solar system must also have something to do with their composition. To generate volcanic flows, for instance, a moon not only must have a source of internal heat but also must be made of material that can be at least partially melted. Models of the chemistry of the primitive solar nebula indicate that the moons of the outer solar system should be mixtures of carbonaceous rock and ices, primarily water ice. The surface temperature of the moons of Uranus is in the neighborhood of 80 degrees Kelvin (−193 degrees Celsius); water ice melts at 273 degrees K. Whatever the heat source of the moons was, theoretical calculations suggest that it is unlikely the internal temperature of such small bodies was ever 200 degrees higher than the surface temperature.

The moons probably contain some



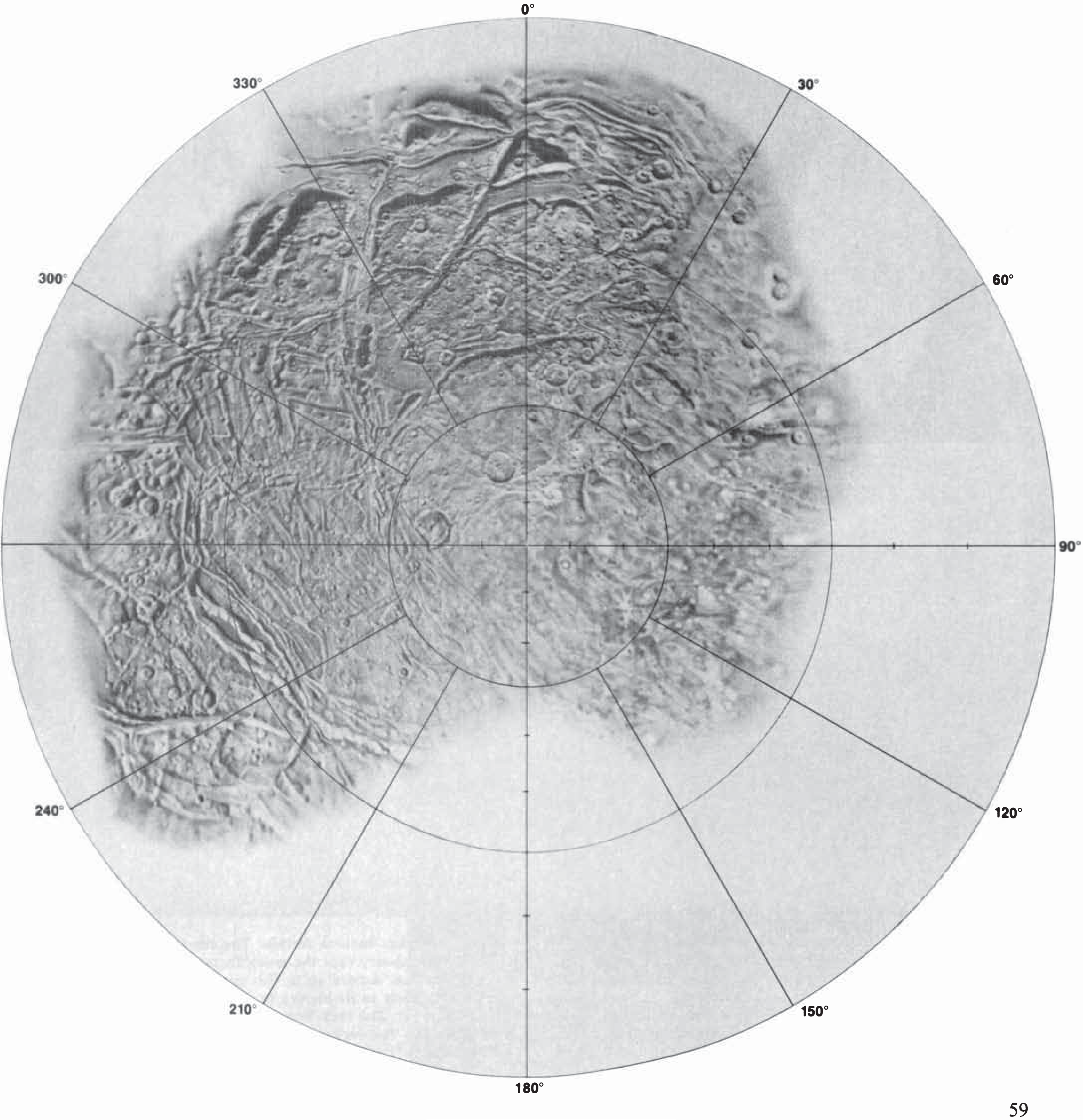


ARIEL displays more evidence of having been volcanically active than any other Uranian moons do. The photograph is a mosaic of images made from a distance of some 130,000 kilometers. The most prominent features are the broad, crisscrossing grabens, or fault valleys, along the equator (at the right in the photograph). The grabens are filled with smooth, sparsely cratered material that was extruded along the axes of the valleys and flowed over the valley floors. The process, a familiar one on the earth, is illustrated at the left. Stretching of the crust causes it to rupture along extensional faults (*1*); next a block of crust drops down along the faults, forming a graben (*2*); finally, partially molten material from the interior of the moon rises into the crack (*3*). The fact that much of Ariel was re-covered after the heliocentric bombardment is indicated by the almost total absence of large craters.

material that is more readily melted than pure water ice. The leading candidates are ammonia hydrate, methane clathrate (a form of water ice in which methane molecules are interspersed in the ice-crystal lattices) and carbon monoxide clathrate. A saturated ammonia-water mixture, for example, has a melting point about 100 degrees lower than that of pure water.

The relative proportions of ice and rock in a moon also influence its propensity for geologic activity. The more rock it has, the stronger is its radiogenic heat source, because the radioactive elements are embedded in the rock. To estimate the amount of rock in a moon one must know its average density, and to know its density one must know its mass with some precision. Estimates of the mass of the Uranian moons made before the *Voyager* flyby proved to be inaccurate, but *Voyager 2* was able to measure the masses of Oberon and Titania precisely. (The measurement procedure was an interesting one. During the weeks before the encounter the moons were continually photographed, because their exact positions were needed in order to navigate the spacecraft. The photographs revealed the tiny perturbing effects of the moons on one anothers' orbits. These perturbations, together with precision radio tracking of the spacecraft, enabled workers to calculate the satellite masses.)

When the measured masses are converted into densities, and when allowance is made for the effects of the moons' own gravitational self-compression, both Oberon and Titania turn out to consist of materials whose average density is between 1.4 and 1.7 grams per cubic centimeter. These

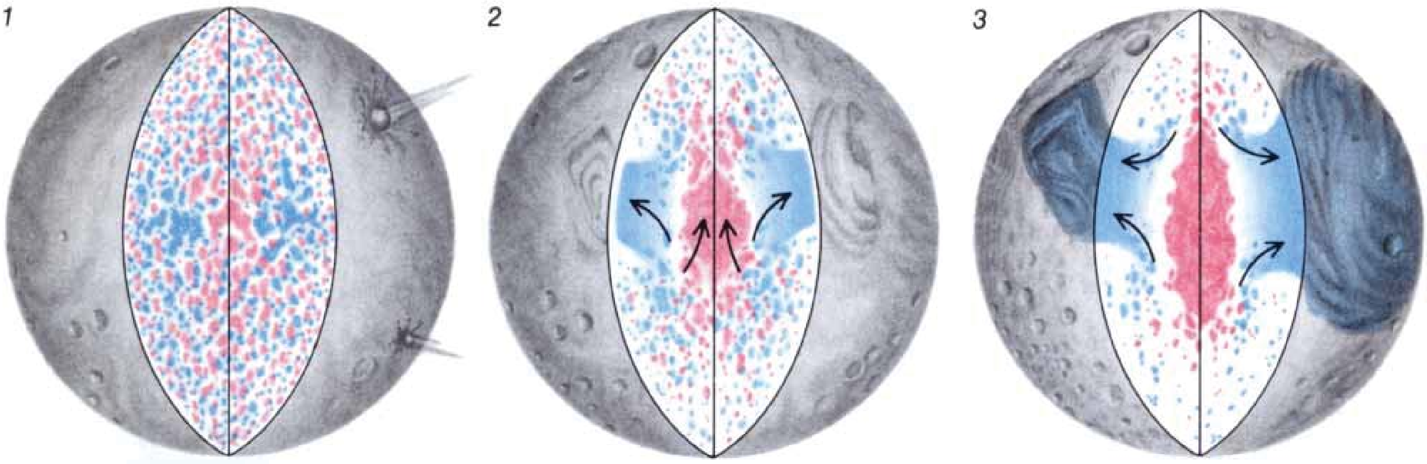


figures imply that the two moons are between 40 and 65 percent rock, which makes them considerably rockier than Iapetus and Rhea, two Saturnian moons of comparable size. The other Uranian moons may have similarly high rock fractions. (One cannot say for sure because the uncertainty about their masses is still too high.) This suggests that radiogenic heating may have been a significant contributor to their geologic activity.

The rockiness of the Uranian moons compared with the Saturnian ones is counterintuitive; simply put, one expects to find more rather than less ice as one moves farther away from the sun. Some models of the solar nebula had predicted that the Uranian moons would be no more than 35 percent rock. Apparently they were wrong.

Various revisions of the models have been proposed. One possibility is simply that the chemical reactions prevailing in the cold outer regions of the solar nebula were different from those in the inner regions. Another possibility, suggested by James B. Pollack of the Ames Research Center, is that the Uranian moons got their rockiness not from the solar nebula but from a gaseous envelope linked to Uranus. David J. Stevenson of the California Institute of Technology has proposed that an envelope rich in rocky materials could have been created by the event that is thought to have given Uranus its unusual orientation: the impact, during the final stage of the planet's accretion, of a body about the size of the earth. The moons would probably have been disrupted by such an impact, and so they must have formed afterward. In the process they may have incorporated rock from the impactor or from the planet itself.

The *Voyager* images have revealed much about the Uranian moons. But they did not reveal immediately or unambiguously why the moons are the way they are: why they are dark and rocky and geologically varied. Nor did we expect them to. Those are problems that will occupy theoreticians for some time. As for us, we are already gearing up for Neptune, for Neptune's large moon Triton and for *Voyager 2*'s next brief but intense encounter, in 1989, with another world.



MIRANDA is seen here from an angle that *Voyager 2* never saw. Because the spacecraft passed so close to Miranda (within 29,000 kilometers), the scale of its rugged topographical features could be deduced from stereoscopic views of the same region from different angles. Miranda is the only moon in the outer solar system for which such detailed topographical information is available. Using these data, workers at the Geological Survey have reprojected the *Voyager* images from new angles in order to highlight various features of Miranda's bizarre terrain. The reprocessed images lend support to the theory that the moon froze in an embryonic stage of differentiation. According to this model, Miranda had enough internal heat early in its history to allow its ice and rock to form agglomerates (*1*). The rock began settling to the core and the ice began rising to the surface (*2*). Eventually large plumes of ice breached the surface, forming the ovoid patterns (*3*). Miranda's heat dwindled before the differentiation process could be finished.