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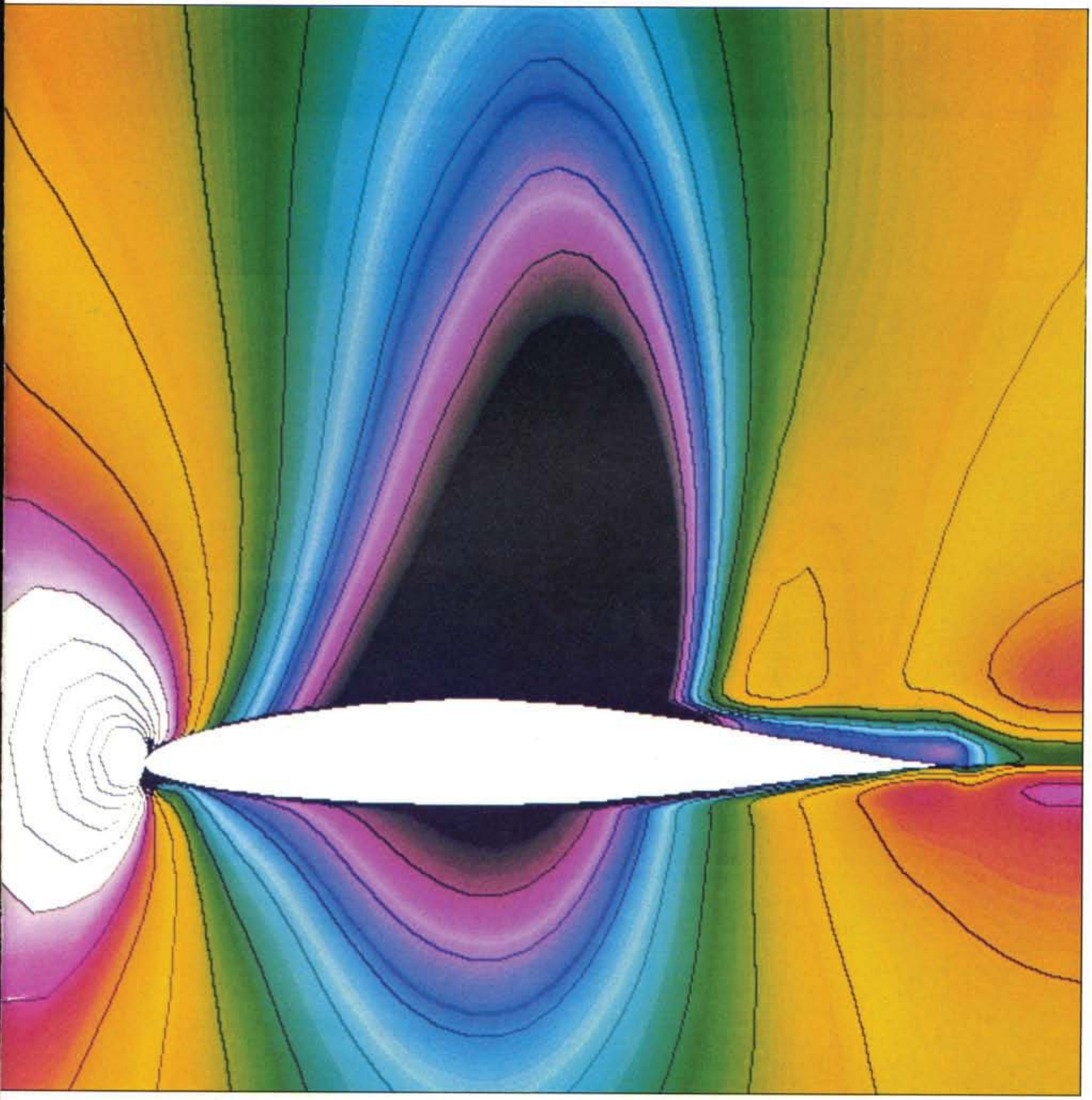

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The Moons of Saturn

The 17 icy bodies that orbit the planet display a surprising range of geological evolution. Many of them show craters more than four billion years old, but one of them has terrain so new that no craters are seen

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Before the spacecraft *Voyager 1* neared Jupiter in March, 1979, only five bodies in the solar system other than the earth had been observed in sufficient detail for their history to be surmised. In essence all of them (Mercury, the moon and Mars and its moons Phobos and Deimos) consist of rocky material. The encounter with Jupiter and its moons doubled the list. Moreover, it marked the first appearance on the list of planet-size moons composed mostly of ices.

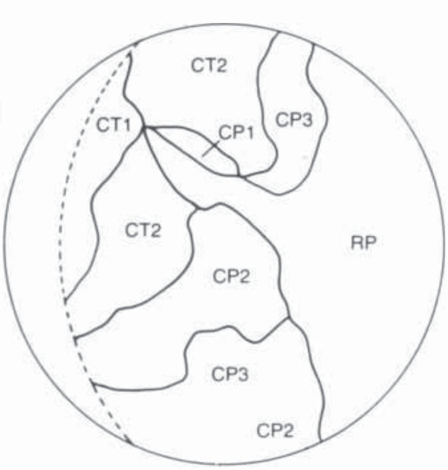
The encounters with the Saturn system doubled the list again. In November, 1980, *Voyager 1* flew past Titan, the largest moon of Saturn, at a distance of only 7,000 kilometers. It passed the smaller moons Mimas, Dione and Rhea at greater distances but nonetheless transmitted high-resolution images of each back to the earth. The trajectory of *Voyager 2* had already been devised to bring the spacecraft closer than *Voyager 1* had come to the moons Iapetus, Hyperion and Phoebe; in addition it would come very close to Tethys and Enceladus. In the months before the arrival of *Voyager 2* near Saturn last August the sequence of observations planned for the spacecraft was altered to provide for observations of several newly discovered moons, three of which were found by *Voyager 1*. In spite of a temporary jam in the mechanism that points the cameras on *Voyager 2*, the mission was successful. In a few short months, therefore, the moons of Saturn have been transformed. Before November, 1980, the ones that were known were no more than dots of light in a telescope. Now they form an array amounting to 17 new worlds.

General Properties

Several generalizations can be made about the moons of Saturn. In the first place only one of them has any appreciable atmosphere. It is Titan, whose atmosphere is opaque to visible light. Since no one has seen the surface of Titan, we have little direct information about its geological evolution. Second, it can be calculated that all but the three outermost moons of Saturn should certainly be in synchronous rotation: they should keep the same face turned toward the planet, just as the moon keeps the same face turned toward the earth. In each such case a planet's gravitation raises a tidal bulge on a moon. Then the gravitational attraction between the bulge and the planet acts as a torque that slows the moon's rotation until the rotation is synchronous. The Voyager images suggest that all but one or possibly two of the moons of Saturn really do rotate synchronously. The definite exception is Phoebe, the outermost moon, which is too small and too far from the planet to lose its spin to tidal forces. It rotates once every nine hours, whereas its orbital period is 13,211 hours, or 1.5 years. The possible exception is Hyperion, the third-outermost moon. The images made of Hyperion by *Voyager 2* cover only a short arc of the orbit of the moon and leave it uncertain whether Hyperion rotates synchronously or not.

Finally, all but two of the moons of Saturn form a regular system of satellites. That is, their orbits are nearly circular and lie in the equatorial plane of the planet. The two exceptions are Iapetus, the second-outermost moon, whose orbit is inclined 14.7 degrees with respect to the equatorial plane, and Phoebe, the outermost, whose orbit is inclined 150 degrees. (In addition the orbital motion of Phoebe around Saturn is in a direction opposite to that of all the other moons.) Three regular systems of satellites are known in the solar system; they consist of the inner moons of Jupiter, the inner moons of Saturn and the five known moons of Uranus. It is probably no coincidence that those planets all have rings. Rings and a regular system of satellites may form naturally as a by-product of the accretion of a giant planet. In any case each regular system of satellites is thought to have formed from the gas, ice and dust around each incipient giant planet, much as (on a larger scale) the planets formed around the sun.

Observations made with telescopes before the Voyager spacecraft arrived showed that among the moons of Saturn only Titan is as large as the four moons of Jupiter discovered by Galileo; the others are smaller than the earth's moon. The Voyager images show that the moons span a range of sizes from the size of asteroids to that of Mercury. The masses of Saturn's moons remain difficult to specify. An analysis of the mutual gravitational effects the moons have on one another has yielded values for some of the masses, and the tracking of gravitational perturbations in the trajectory of the Voyager spacecraft as they



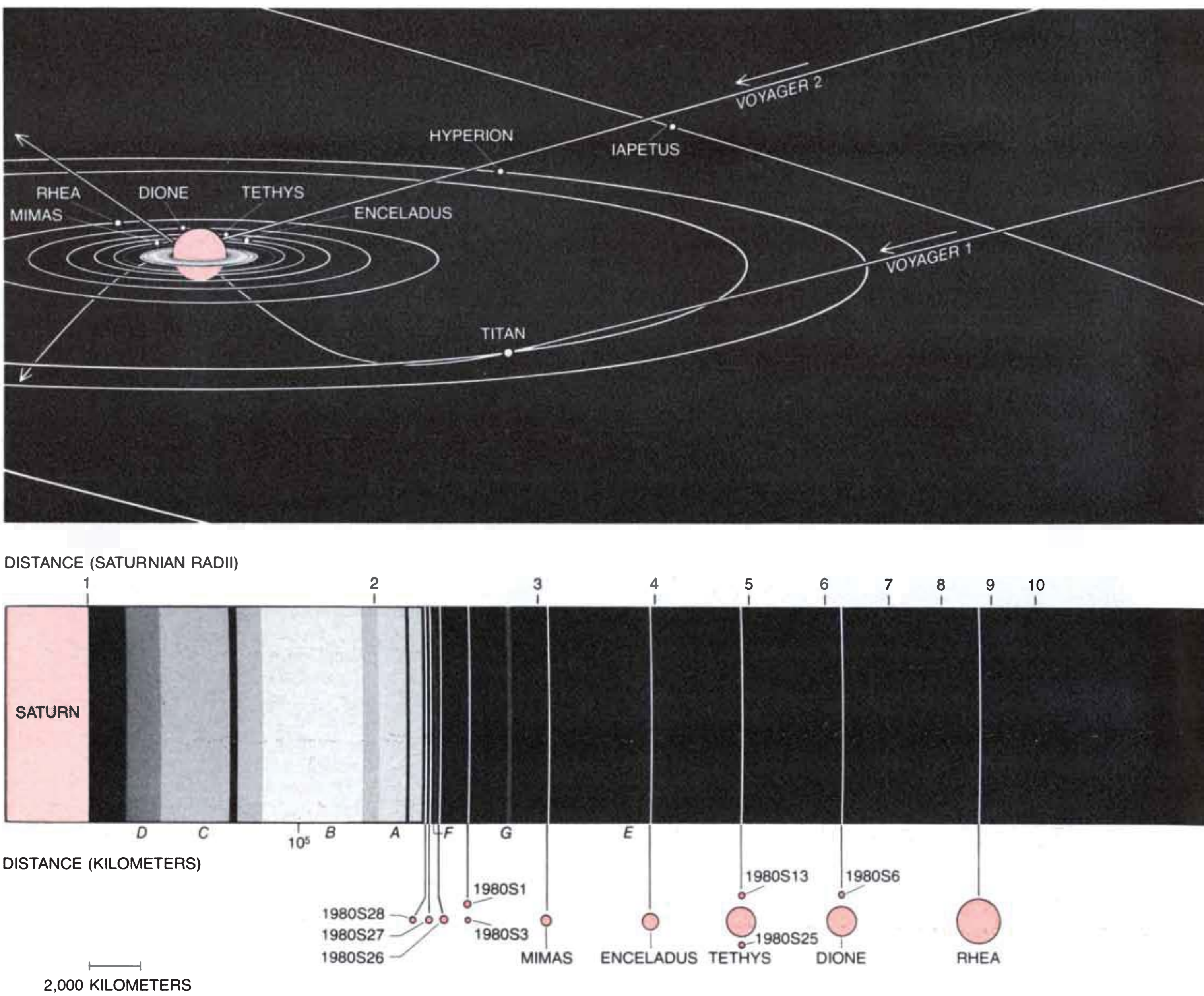
SATURNIAN MOON ENCELADUS was photographed last August 25 by the spacecraft *Voyager 2*. It is some 500 kilometers in diameter and is seen here at a range of 119,000 kilometers in an image that has been processed by computer so that the surface topography stands out. Six different terrains are distinguished. The heavily cratered terrains called *CT*1 and *CT*2 are the oldest; many of their craters are thought to represent the bombardment of Enceladus and other Saturnian moons by debris in orbit around Saturn. The debris was left over from the accretion of the planet, its moons and its rings. The cratered plains *CP*1, *CP*2 and *CP*3 are intermediate in age. The ridged plain *RP* is the youngest; on one hypothesis it lacks visible craters because it consists of upwelling fresh material.

passed among the moons yields new values and refinements of some of the earlier ones. It seems clear from the various measurements that the moons of Saturn all have densities of less than two grams per cubic centimeter. In fact, several have densities of less than 1.5 grams per cubic centimeter. Such values suggest that the moons are composed mostly of ice. For most of Saturn's moons a composition of 30 to 40 percent rock and 60 to 70 percent ice by weight would match the calculated density. Only Titan is large enough for its gravitational self-compression to affect its density appreciably. When this self-compression is taken into account, the density estimated for Titan—1.9 grams per cubic centimeter—becomes compatible with a mixture of half rock and half ice.

In one sense the calculated densities are curious. Among the planets of the solar system one finds a trend toward greater density with decreasing distance from the sun, and among the moons of Jupiter one finds a trend toward greater density with decreasing distance from the planet. Such trends are attributed to the influence of the heat from the central body on the temperature of the gas and dust that surrounded it at the time its satellites formed. In the case of Jupiter it appears that ice was unstable in any large quantities at radial distances from the planet less than the distance of the orbit now followed by Ganymede.

In spite of the uncertainties in the measurements no similar trend of density is evident among the moons of Saturn. Instead the current determinations of the values of the densities are consistent with a composition of rock and ice that is similar in all Saturn's moons except for more or less random variations in the exact proportions. On the other hand, the densities of Saturn's moons in general are less than those of Jupiter's. This suggests a greater proportion of ice. The relative lack of rocky material is explained by models of Saturn's history developed by James B. Pollack and his colleagues at the Ames Research Center of the National Aeronautics and Space Administration. The models suggest that rocky material near Saturn was swept into the incipient planet as it contracted before its moons began to form some 4.5 billion years ago.

In any event the surfaces of the moons of Saturn suggest the presence of ice.



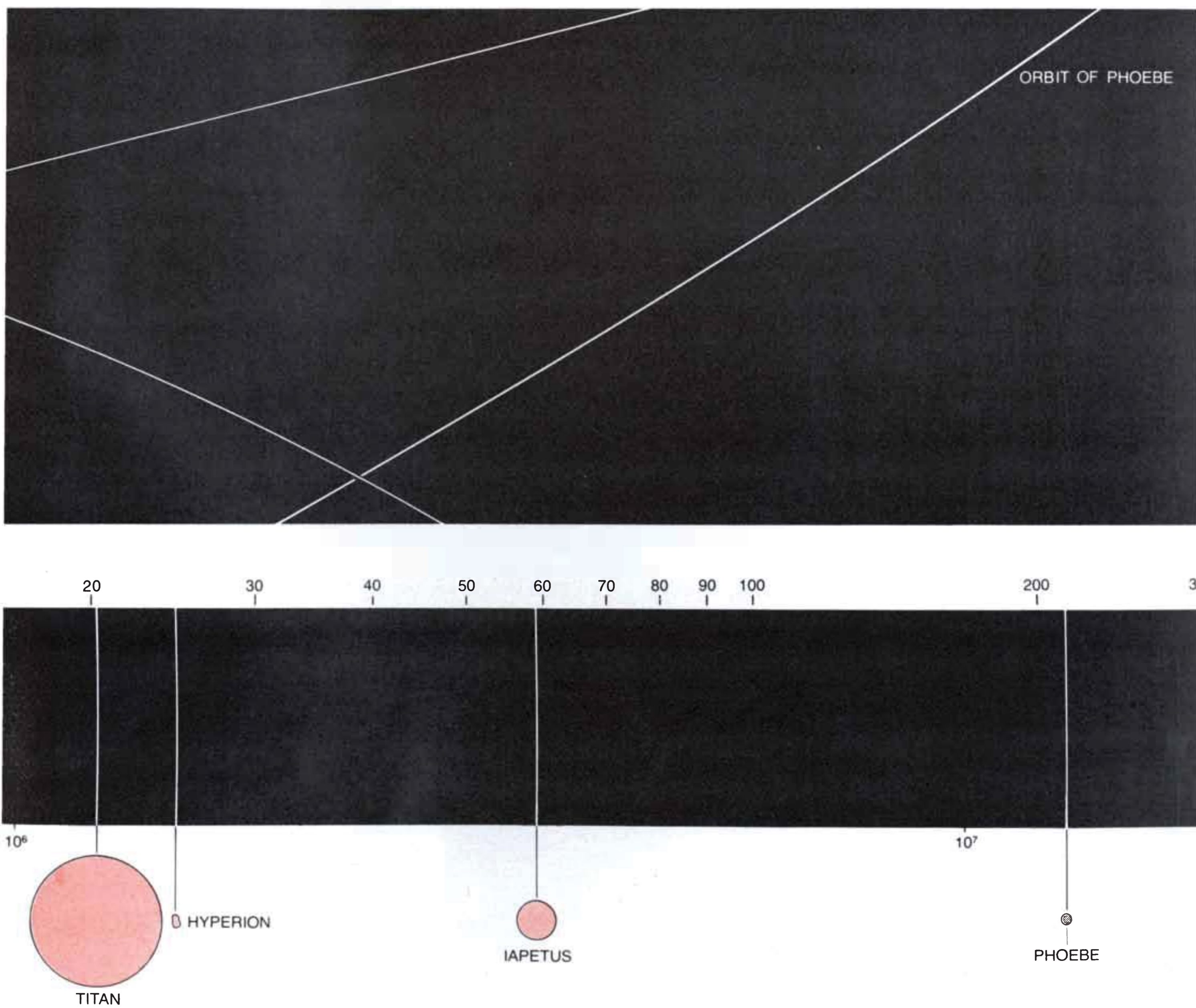
KNOWN MOONS OF SATURN are 17 in number. The top panel shows their orbits. All but two of them lie in the equatorial plane of the planet, which is also the plane of the planet's rings. The exceptions are Iapetus (with an orbit inclined by 14.7 degrees) and Phoebe (with one inclined by 150 degrees). Phoebe's rotation about Saturn is clockwise; all the other moons go counterclockwise. The top panel also shows the trajectory followed by *Voyager 1* in November, 1980, and the one followed by *Voyager 2* last August. The middle panel shows the orbits of the moons on a logarithmic scale; the numbers on the scale are distances from the center of Saturn. Each of the

Spectra of the solar radiation reflected by the moons in the near infrared show its absorption at wavelengths characteristic of water frost. Moreover, measurements made by the Voyager spacecraft show that most of the moons reflect between 60 and 90 percent of the radiation that hits them. With an albedo, or reflectance, of nearly 100 percent, Enceladus is the most reflective body in the solar system. If it were at the same distance from the sun as the earth's moon, it would be about five times as bright. Water ice is highly reflective.

The ubiquity of ice in the outer solar system was not entirely unexpected. For one thing, the vapor pressure of water ice (that is, the tendency of the ice to sublimate and lose vapor to space) depends strongly on temperature. Hence at distances from the sun less than the distance of the asteroid belt between the orbits of Mars and Jupiter an unprotected mass of ice will evaporate in a time quite short compared with the age of the solar system. At greater distances a mass of ice will be stable for billions of years. In addition most models of how the solar system formed predict that water should be a major constituent of a body that accreted at low temperatures.

Specifically, if a gas whose composition is much like that of the sun is cooled under the conditions of temperature and pressure thought to have prevailed in the early solar system, some of the oxygen in the gas will combine with silicon to form silicate rock at relatively high temperatures. When the elemental silicon is exhausted, however, a substantial amount of oxygen will remain. As the temperature continues to decrease it will combine with hydrogen, the element most abundant in the gas. Thus water will form. It emerges from such models that a moon condensing at low temperatures should have much the same proportions of rock and ice as those inferred for Jupiter's moons and Saturn's moons from the estimates of their densities.

One might suppose an icy moon would be no more interesting geologically than a cratered ice cube. Ice, however, has a melting point far lower than that of rock, so that relatively little is needed to melt the interior of an icy moon in the outer solar system. On this basis it was suspected even before the Voyager missions that such moons



moons discovered recently turns out to have a dynamical vagary. The moon 1980S28 lies near the outer edge of the *A* ring; 1980S27 and 1980S26 bracket the *F* ring, and 1980S1 and 1980S3 have orbits that differ by less than the sum of the diameters of the moons (hence they are "co-orbital"). Finally, 1980S13 leads Tethys by 60 degrees, 1980S25 trails Tethys by 60 degrees and 1980S6 leads Dione by 60 degrees. Each of the three occupies a position of stability studied by Joseph Louis Lagrange in the 18th century and today called a Lagrange point. They are the first known Lagrangian moons. At the bottom of the illustration all the moons of Saturn are shown to scale.

might show signs of geological activity. It was also proposed that the moons of the outer solar system might incorporate substances such as ammonia hydrates and the compounds of methane and water known as clathrates. The interior of a moon incorporating such material would melt even more readily than a moon consisting of rock and water ice alone. The results of the Voyager missions surpass the speculations. Hyperion, Mimas and Enceladus, for example, are much the same size, but they display a range of geological evolution far broader than one would have thought was likely.

The New Satellites

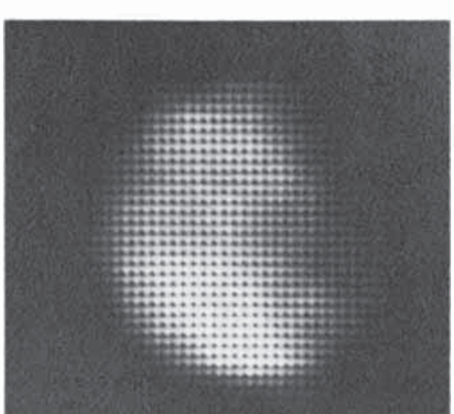
The moons of Saturn discovered in the past decade have dynamics that are unusual in one way or another. Consider 1980S28, the innermost moon in the set and also the innermost known moon of Saturn. It was discovered by *Voyager 1* just beyond the outer edge of Saturn's *A* ring. 1980S28 is an elongated body whose diameter is about 40 kilometers. One hypothesis suggests that its gravitational field does much to sculpture the sharp outer edge of the ring. Somewhat farther out from Saturn are the pair of small moons 1980S27 and 1980S26. They too were discovered by *Voyager 1,* although it can now be recognized that at least one of them may have affected the counts of charged particles made by the *Pioneer 11* spacecraft near Saturn in September, 1979. Between their orbits lies the multistrand *F* ring. The gravitational fields of the moons may well confine the ring. For that reason they are called the shepherd moons.

About 10,000 kilometers beyond the *F* ring, or roughly halfway between the *F* ring and the *G* ring, are the "co-orbital" moons 1980S1 and 1980S3. The French astronomer Audouin Dollfus photographed one of them at the Pic du Midi Observatory in 1966. Today it is difficult to say which one it was. In 1978 John W. Fountain and Stephen M. Larson of the University of Arizona determined that there were two moons. Then in 1979 *Pioneer 11* made an image of one of them. The Voyager spacecraft made images of both. The mean orbital radii of 1980S1 and 1980S3 differ by less than the sum of their diameters. Hence their orbital velocities are similar but not quite identical: the inner moon slowly overtakes the outer one. As they approach each other the gravitational attraction between them alters their angular momentum. The inner moon gains momentum; it moves into a larger orbit, where its orbital speed is reduced. The outer moon loses momentum; it moves into a smaller orbit, where its orbital speed is increased. In short, the two moons change places; the inner moon becomes the outer one and begins to fall behind. About once every four years the celestial dance is repeated and the two change places again.

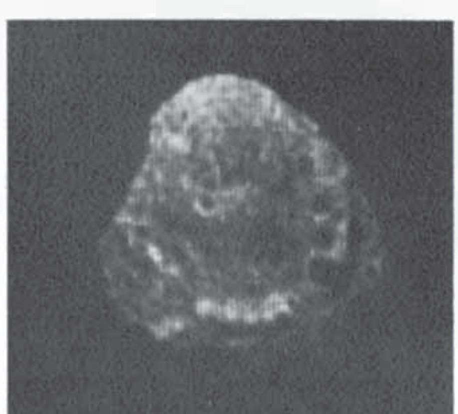
Three other new moons of Saturn were found by earth-based telescopes in 1979 and 1980, a time when Saturn's rings were edge on as they are seen from the earth. This orientation greatly reduces the effect of scattered light from the rings when Saturn is viewed in a telescope and allows the detection of faint bodies close to the planet. Two of the three new moons share their orbit with Tethys. One of them maintains a position about 60 degrees ahead of Tethys; it was discovered by a group led by Bradford A. Smith of the University of Arizona. The other stays about 60 degrees behind Tethys; it was discovered with the aid of a prototype of a planetary camera system designed for the telescope that the U.S. plans to put in orbit around the earth. The third moon stays about 60 degrees ahead of Dione; it was discovered by two French astronomers: P. Lacques of the Pic du Midi Observatory and J. Lecacheux of the Paris Observatory.

Each of the positions occupied by these moons is a point of dynamical stability of the kind first studied by the French mathematician Joseph Louis Lagrange and today called a Lagrange point. In 1772 Lagrange noted that in a system consisting of one body in orbit around another (say the moon around the earth) there are five positions at which a third body can lie undisturbed. Three of the positions are unstable: a body at any one of them is readily driven from it by the influence of gravitational forces other than those exerted by the two bodies that set up the system. The three positions lie (1) inside the orbit of the satellite, (2) outside the orbit and (3) at the point in the orbit opposite the satellite itself. The remaining two positions—the ones on the orbit 60 degrees ahead of the satellite and 60 degrees behind—are quite stable: a body that occupies either one of them will merely drift back and forth along its orbit under the influence of perturbing forces. It has long been known that the groups of asteroids called the Trojans occupy the two Lagrange points 60 degrees from Jupiter along the orbit of the planet around the sun. The three bodies at Lagrange points near Saturn are the first known Lagrangian moons.

In contrast to their dynamical vagaries the newly discovered moons have much the same appearance. Each is rather small, and almost all of them are quite irregular in shape. The irregularity tells much. It suggests that each moon arose from the fragmentation of a larger body. And since a small, cold, icy moon is strong enough to keep itself from being pulled into a sphere by its gravitational self-attraction, the irregular shapes suggest that these moons have not been heated significantly since the time they took their current form.



PHOEBE, the outermost moon of Saturn, was photographed by *Voyager 2* at a range of 2.2 million kilometers. Its curious orbit and its low reflectivity (about 5 percent) suggest that it formed elsewhere in the solar system and then was captured by Saturn's gravity. Phoebe is about 200 kilometers in diameter.



HYPERION, the third-outermost moon, was photographed by *Voyager 2* at a range of 500,000 kilometers. It is an irregular body about 400 kilometers long and 220 kilometers wide. It is four to six times brighter than Phoebe. The concavities along the margin of this image of Hyperion are probably craters.

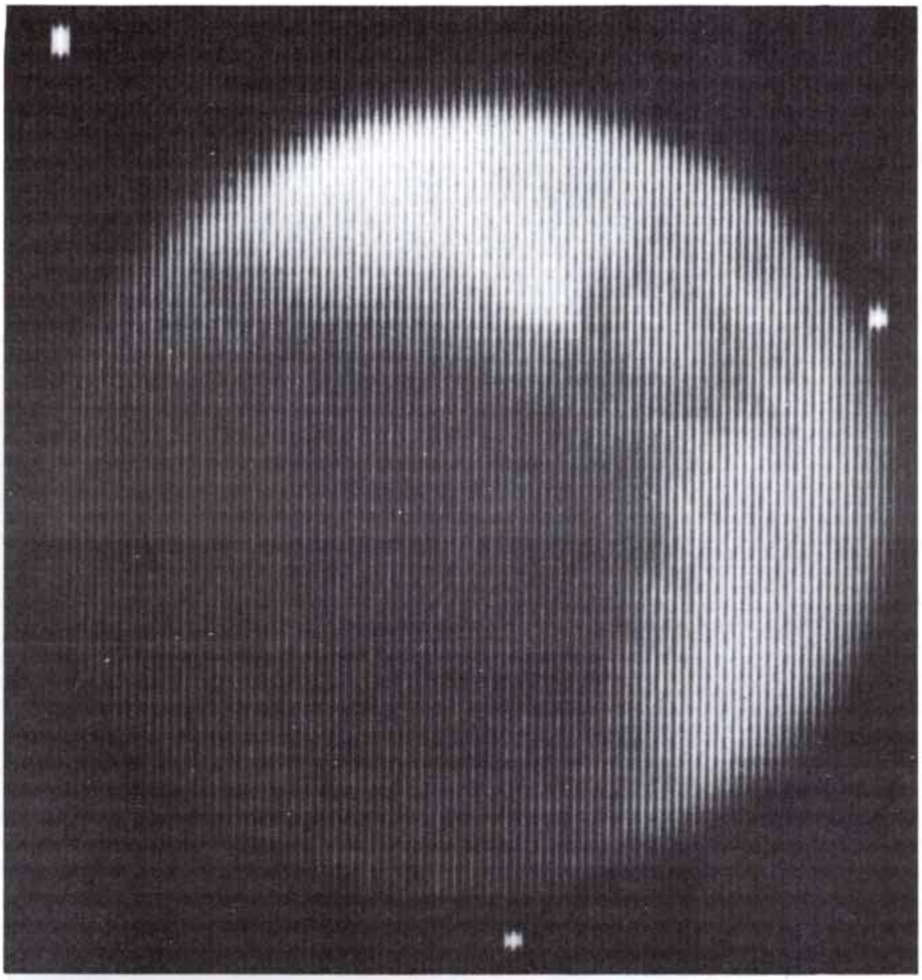
Iapetus

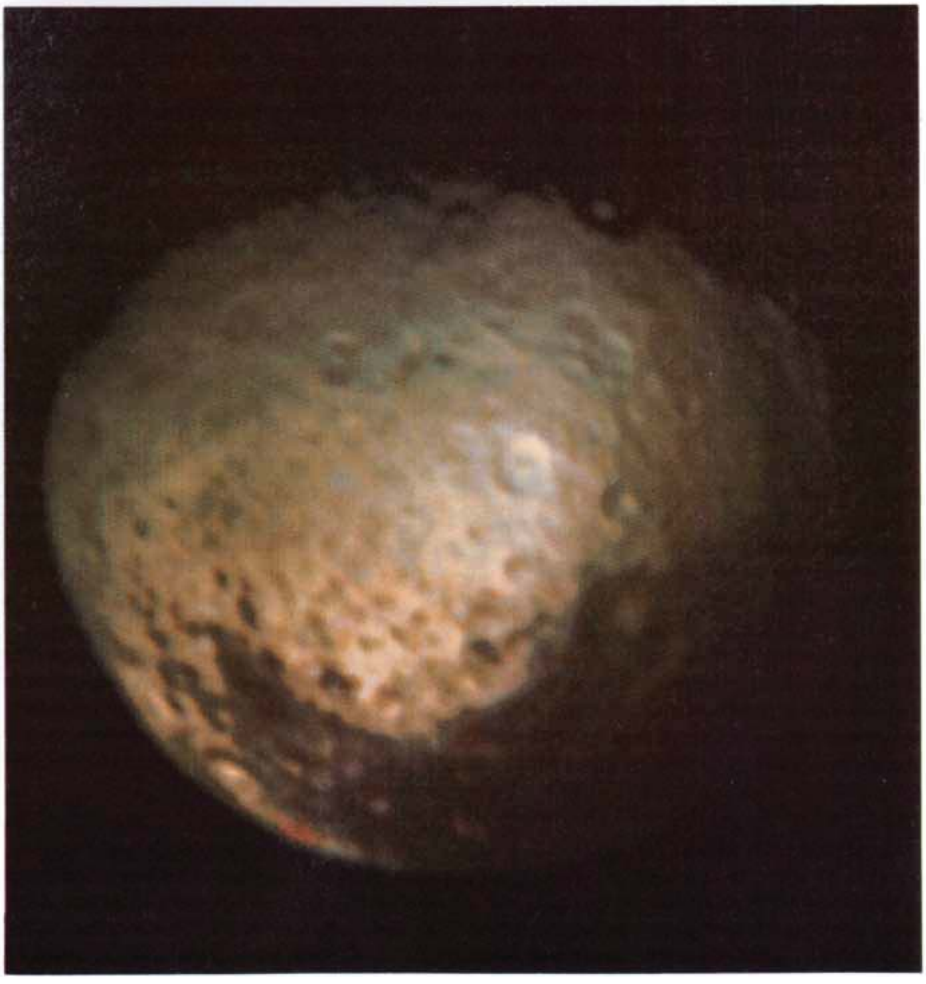
Iapetus and Rhea are the second-largest of Saturn's moons; they have a nearly identical diameter of about 1,500 kilometers. They move in quite different orbits. The orbit of Iapetus lies about 60 Saturnian radii (R_s) from the center of Saturn, that of Rhea about 9 R_s. They bracket the orbits of two other moons of Saturn, namely Titan and Hyperion. As we have noted, the orbit of Iapetus is inclined.

Iapetus has a density of about 1.1. This means its density is almost as low as that of pure water ice. Since it keeps the same face turned toward Saturn, its trailing hemisphere (the side facing backward with respect to its orbital motion) is always the same part of the surface. The trailing hemisphere is bright. In the visible region of the electromagnetic spectrum its albedo is almost 50 percent. In contrast the leading hemisphere is extremely dark: its albedo is only 3 to 5 percent. This difference was noted in the 17th century by Jean Dominique Cassini, the discoverer of Iapetus, who found he could see the body on one side of Saturn but not the other. Among the few materials whose albedo is only a few percent are lampblack and the primitive meteorites called carbonaceous chondrites.

The peculiar pattern of darkness and brightness on Iapetus has suggested that dark material falling from space coats what amounts to the prow of the moon. In 1974 it was further suggested by Steven Soter of Cornell University that the source of the material is Phoebe. Phoebe had long been taken to be a moon of low albedo; observations made with earth-based telescopes show that its color is similar to that of many dark asteroids. The idea, then, is that dark matter is kicked off Phoebe by the impact of micrometeoroids. Then the particles of the matter come under the influence of what is called the Poynting-Robertson effect. Specifically, electromagnetic radiation leaves each particle because the particle reflects some of the radiation incident on it and because the particle absorbs some radiation and reemits it later. In either case the radiation leaving the particle in the direction of the particle's orbital motion around Saturn undergoes a Doppler shift that gives it a higher frequency (and thus more energy and momentum) than that of the radiation leaving in the opposite direction. The net result is that the particle loses orbital angular momentum and slowly spirals inward. As it falls (the argument concludes) it is swept up by Iapetus.

The images of Phoebe made by *Voyager 2* show some detail of Phoebe's sur-





IAPETUS was photographed by *Voyager 1* at a range of 3.2 million kilometers and nine months later by *Voyager 2* at a range of 1.1 million kilometers. The image made by *Voyager 1* (*top*) shows the side of the moon that always faces Saturn. (Iapetus and most other Saturnian moons keep the same face turned toward Saturn, just as the earth's moon keeps the same face turned toward the earth.) Iapetus is moving toward the left; the leading hemisphere of Iapetus (the hemisphere facing in the direction of the orbital motion of the moon) is dark. A ring of dark material extends, however, into the bright trailing hemisphere. The image made by *Voyager 2* (*bottom*) shows the side of the moon that always faces away from Saturn. The north pole of the moon coincides roughly with the large crater astride the border between day and night on Iapetus (the terminator), which crosses the top of the image. The dark leading hemisphere is at the right. An equatorial band of darkness extends into the trailing hemisphere. The sharp and complex boundary between bright and dark regions on Iapetus militates against the proposal that dark matter fell from space onto the leading part of the moon. It suggests instead that the dark matter is an extrusion from within Iapetus.

face. Phoebe emerges as being roughly spherical and having an albedo of only about 5 percent. In both of these attributes (and in its inclined, retrograde orbit) it proves to be quite different from the co-orbitals, the ring shepherds and the Lagrangian moons of Saturn. Phoebe may indeed be a captured dark asteroid, unchanged since it accreted early in the history of the solar system. Perhaps it is a primordial body that was ejected from the inner solar system by the gravitational field of the growing planet Jupiter and took up an orbit around Saturn.

In themselves the Voyager images of Phoebe cannot make it plain whether Phoebe dusted the dark leading hemisphere of Iapetus; the idea is still being debated. One test of the idea involves Hyperion, the next moon inward from Iapetus. The test rests on the assumption that Hyperion should have been dusted by material kicked off Phoebe that Iapetus failed to sweep up. The images made by *Voyager 2* show Hyperion to be a remarkable little moon. It is nearly the size of Mimas, a spherical moon with a radius of about 200 kilometers, and yet it is markedly elongated: its short axes are only about three-fifths the length of its longest axis. Hyperion is one of the largest bodies in the solar system that has an irregular shape. (The asteroid Hector is one of the very few other such objects.) An analysis of the Voyager images indicates that Hyperion is somewhat darker than most of the moons of Saturn: its albedo is 20 to 30 percent. This finding is consistent with a dusting by matter from Phoebe. Hyperion appears, however, to lack a dark leading hemisphere. The problem with searching for one is that it is not yet established whether Hyperion rotates synchronously.

An answer to the question of whether Phoebe dusted Iapetus therefore awaits in part the determination of the rotation rate of Hyperion from observations made with ground-based telescopes. Meanwhile the findings of Dale P. Cruikshank and his associates at the University of Hawaii at Manoa may have got the idea into trouble on other grounds. Cruikshank's group has found from telescopic observations that the color of Phoebe and the color of the dark leading hemisphere of Iapetus are different. The dark regions on Iapetus are much redder than Phoebe throughout the visible and the near-infrared region of the spectrum. This makes it difficult to favor a scheme in which material from Phoebe simply coats the dark part of Iapetus without having undergone some kind of change.

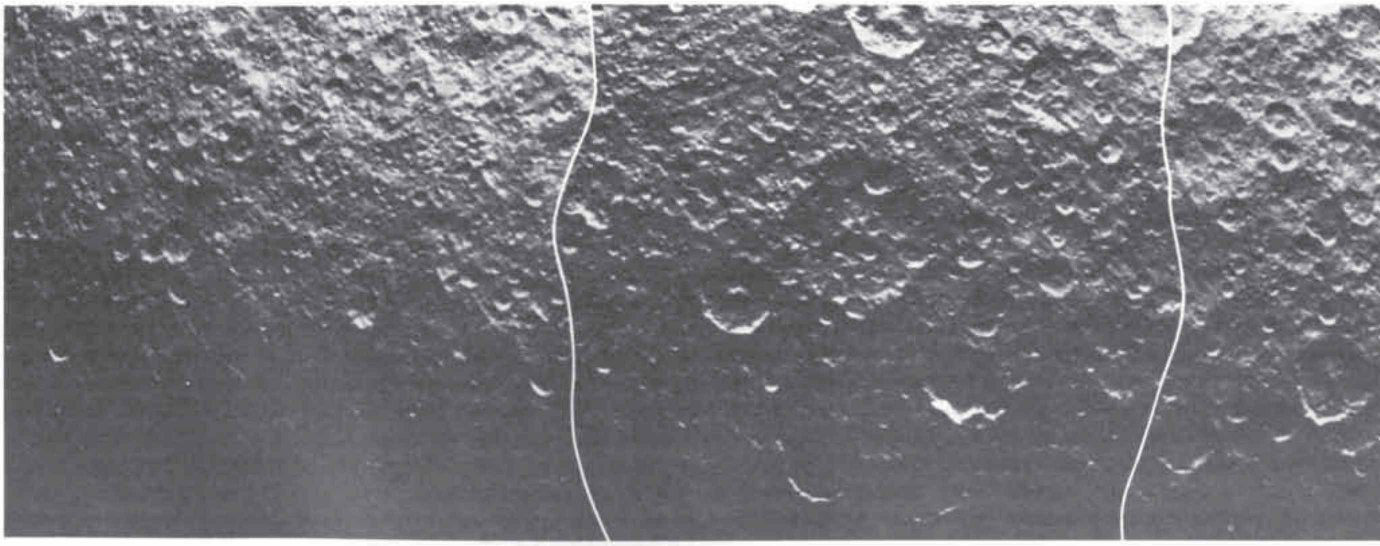
The images of Iapetus made by the Voyager spacecraft also tend to subvert the hypothesis that it was dusted by matter from Phoebe. *Voyager 1*'s best image of Iapetus was made at a range of 2.5 million kilometers. The image showed only those features on Iapetus that are more than 50 kilometers across. Even so, a clue to the history of the body emerged. A ring of dark material about 100 kilometers in diameter was found to straddle the border between the hemispheres. It strongly resembles the rings in craters along the margin of large volcanic flood plains on the moon and Mars. Such rings formed there when dark volcanic melts flowed into impact craters and filled each one around its central peak. Perhaps the dark ring on Iapetus formed by a similar process when fluid extruded from the interior of the body darkened half of it. Clearly it is unlikely that a feature with such a peculiar geometry as that of a dark ring could have been formed by matter falling from space.

Voyager 2 made a series of images of Iapetus at a resolution three times greater than that of the images made by *Voyager 1*. The single best image is of the north polar region, mostly in the bright trailing hemisphere. It shows that the trailing hemisphere is heavily cratered. Many of the craters have a dark floor. Such floors resemble the dark floors of craters on the highlands of the earth's moon, which are thought to have formed when volcanic material flowed out over them. Taken together, the dark-floored craters in the trailing hemisphere and the sharp definition and complexity of the boundary between dark and bright terrain imply a history of eruptions from the interior of Iapetus. That is not to say the erupting material resembles any ordinary lava. One can speculate that it is a fluidized slurry of a mixture including ammonia, ice and something dark. The low albedo of the material suggests that whatever its origin, the dark stuff is rich in organic substances such as are found in primitive meteorites.

RHEA was photographed by *Voyager 1* at a range of 1.7 million kilometers. Here the image of the moon is shown in false color. The trailing hemisphere (seen here) is marked by bright wisps that do not seem to follow a pattern laid down by craters. The leading hemisphere is bland.

Rhea

The distant views of Rhea transmitted to the earth by *Voyager 1* as the spacecraft approached the moon showed a bright, bland leading hemisphere marked only by what appears to be a large and relatively recent impact crater. The trailing hemisphere is different. It shows a complex pattern of bright swaths on a background darker than the leading hemisphere. The swaths are thought to result from internal activity. Perhaps the bright material was extruded along lines of fracture at the surface. In any event the bright swaths fail to follow the kind of pattern that cratering would lay down on the surface. The zone containing the swaths is confined within a small circle at the center of the trailing hemisphere. The boundary be-



RHEA'S NORTH POLE was photographed by *Voyager 1* at a range of 80,000 kilometers. The pole itself is at the middle of the arc the terminator describes across this mosaic. The terrain to the west of the pole (toward the right in this image) is marked by large craters; in the terrain to the east such craters are missing. Presumably the large craters were made early in the history of the moon; the small craters both east and west were made later, after geological activity had given the terrain to the east of the pole a fresh, uncratered surface.

tween this zone and the bland leading hemisphere is diffuse.

The high-resolution views of Rhea made by *Voyager 1* show the equatorial region of the leading hemisphere somewhat to the east of the putative large, fresh impact crater. The best views show the north pole of the body, which *Voyager 1* flew over at a distance of only 59,000 kilometers. In each view Rhea is found to have a densely cratered surface much like the cratered highlands on the moon and Mercury. The principal difference is that the large, fresh craters on the moon and Mercury are surrounded by blankets of ejecta; the craters on Rhea are not. Presumably Rhea's weaker gravity is responsible. If Copernicus, a large crater on the earth's moon, had formed on Rhea, its ejecta would have been spread over most of the body's surface. On the earth's moon most of the ejecta lie no farther away than a few times the radius of the crater.

The nature and the origin of the bodies that cratered Rhea can be surmised from a mosaic of images showing the body's north polar region. At first the entire region appears to be uniformly pitted with craters. A closer examination shows that the western two-thirds of the polar mosaic is marked by a collection of craters with diameters ranging from 30 to 100 kilometers and in addition a dense population of smaller craters. The smallest ones visible are a few kilometers across. If other craters are smaller still, they are below the limit of resolution. The eastern third of the mosaic is also marked by small craters, but the larger craters are missing. A few subtle depressions in the surface are visible. They suggest that the larger craters in the east were filled or buried.

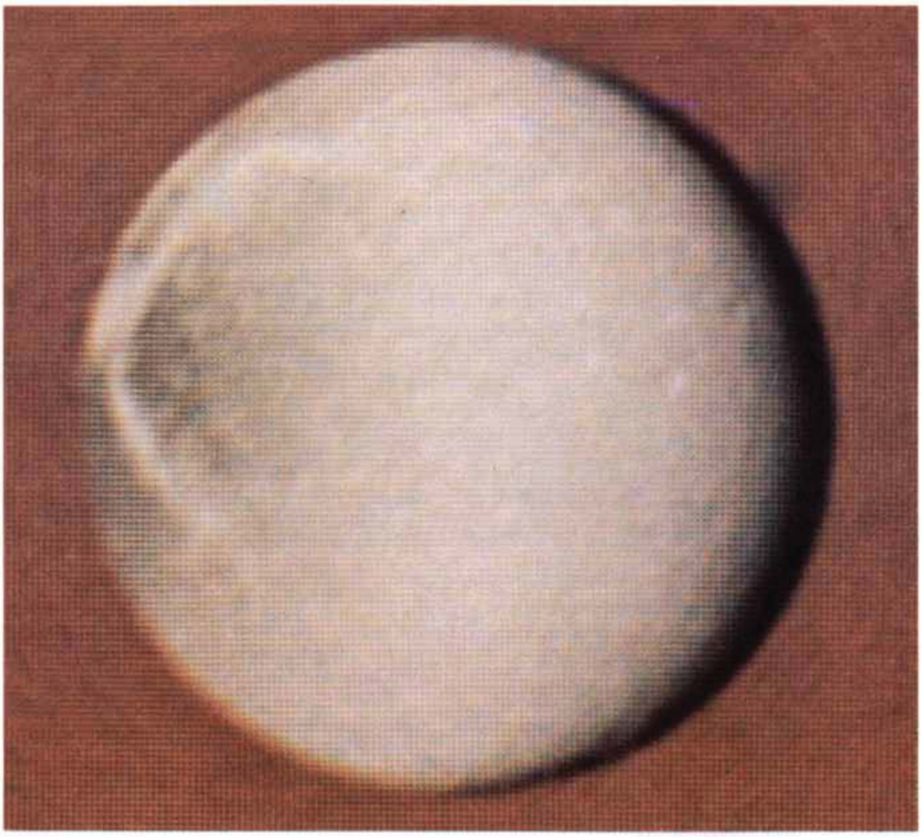
The difference between the two terrains implies a period of cratering in which projectiles with a wide range of energy formed craters with a wide range of sizes. At some point the remaining projectiles whose impacts could form large craters (craters greater than 50 kilometers in diameter) were swept up. The bombardment by the objects that formed the smaller craters continued. Meanwhile part of Rhea's surface was regenerated, perhaps by fluid extrusion from the interior or perhaps by the flow of a slurry of material driven to the surface by the pressure of gases accumulating within the moon. The resurfacing included the eastern third of the polar terrain. Estimates of the rate at which Rhea is being cratered by comets and asteroids today indicate that few of the visible craters (both large and small) in the images are recent. Hence most of the cratering must have come early in the history of the solar system, and it must have been intense. The projectiles could have been remnants of the accretion of gas and dust in orbit around the sun. They could have been remnants of the accretion of gas and dust in orbit around Saturn. They could also have come in pulses as the debris from bodies that collided in the early Saturnian system.

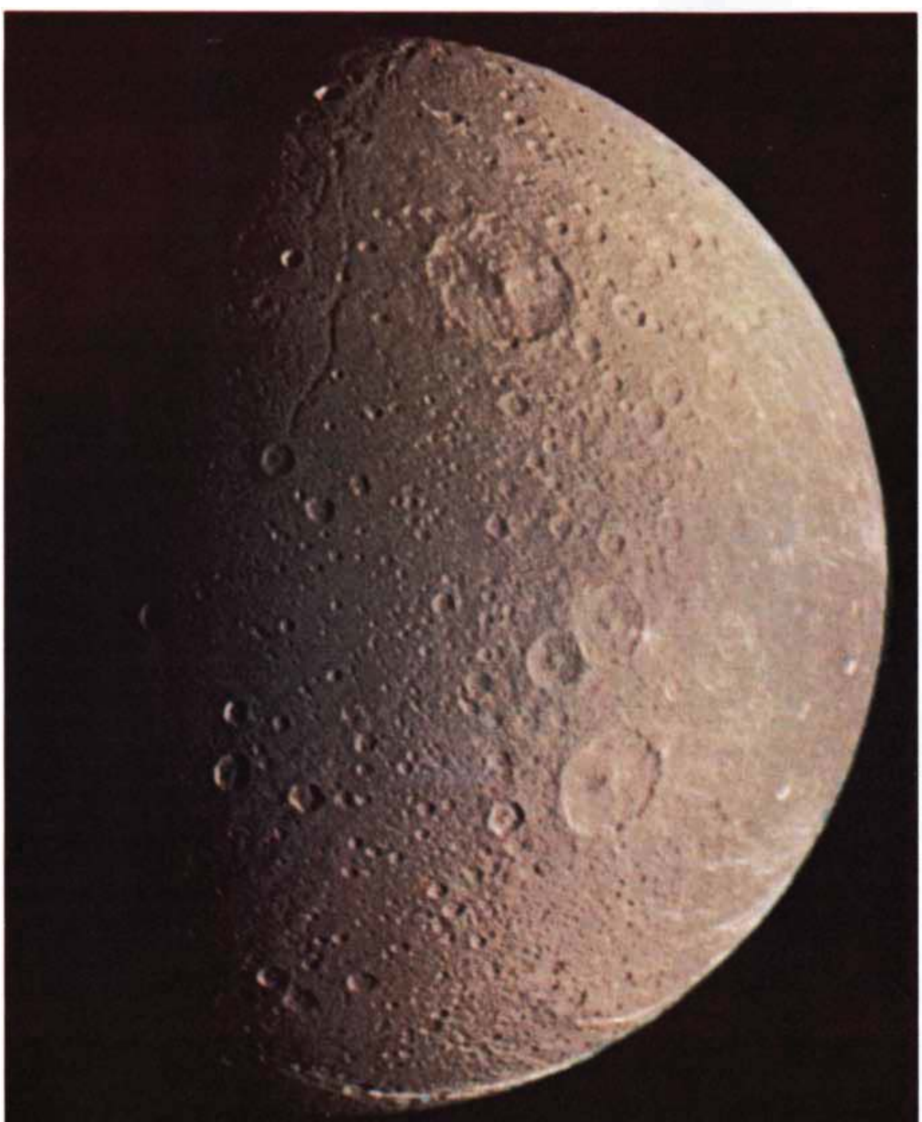
Dione

In sum, the appearance of Rhea suggests that at least two populations of projectiles marked the surface. The appearance of Dione, the next moon inward from Rhea, allows more detailed deductions. Dione travels in orbit around Saturn at a distance from the planet's center of 6.2 R_S. Its diameter is 1,100 kilometers. With a density of 1.5 grams per cubic centimeter it is the densest of Saturn's moons except Titan. The distant views of Dione made by *Voyager 1* showed a striking asymmetry between the leading and the trailing hemispheres. In the trailing hemisphere a network of intersecting bright streaks on a dark background was visible. It looked much like the trailing hemisphere of Rhea. The leading hemisphere was uniformly bright. Again the region of complex variations in albedo was confined within a small circle at the center of the trailing hemisphere, and again the boundary of this region with the bland leading hemisphere was diffuse.

Closer views of the trailing hemisphere made by *Voyager 1* showed that craters between 50 and 100 kilometers in diameter were crossed by the streaks. Therefore the streaks must have formed well after the torrential bombardment the craters imply. All things considered, the large craters on Dione and on parts of Rhea (including the western two-thirds of the polar mosaic) resemble the highland craters found on the earth's moon, Mars and Mercury. We shall refer to the projectiles that made such craters in the Saturnian system as Population I. The most likely hypothesis is that they resulted from the agglomeration of matter left in orbit around the sun after the solar system formed.

The closer views of Dione also showed plains where the density of cratering is far lower than it is on the "highlands." On the plains, however, the proportion of small craters to large ones is far higher. The proportion is that of the eastern third of the polar mosaic of Rhea. On both the plains of Dione and the terrain east of the north pole on Rhea the distribution of sizes among the craters resembles that of the craters surrounding the principal craters on the moon. It also resembles that of the craters surrounding the places on the earth where nuclear devices have been tested. In general the prevalence of small craters suggests the pocking of a landscape by the ejecta from the impacts of larger projectiles or by the fragments pro-



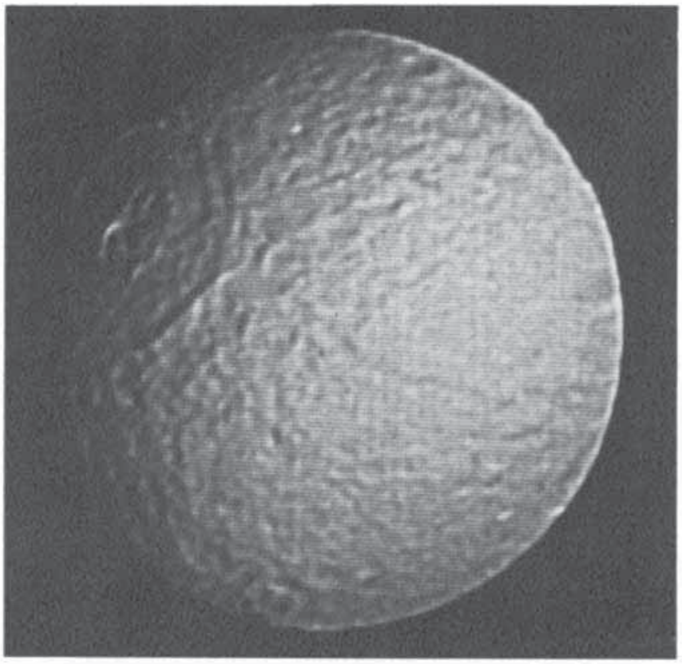


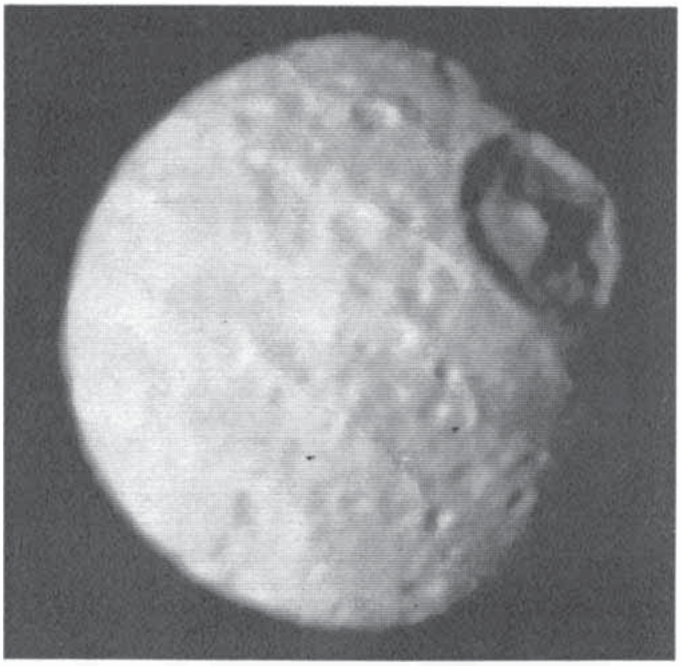
duced by collisions between large bodies. With Dione and Rhea it seems likely the small craters were made by the debris from bodies that collided within the Saturnian system. Presumably, therefore, certain regions of Dione and Rhea bear a record of primordial cratering; other regions were resurfaced by material from the interior that buried the oldest craters. The resurfaced regions were then pocked by a second bombardment. We shall refer to the bodies in the second bombardment as Population II.

A problem remains. The "highlands" bearing evidence of cratering by Population I and the plains bearing evidence of cratering by Population II show no correlation with the global pattern of albedo recorded by *Voyager 1* at a distance from Dione and Rhea. On Dione, for example, the leading hemisphere, which was uniformly bright and bland in the distant imagery, turns out at high resolution to have both highlands and plains. What, then, caused the global albedo pattern? Some calculations made by Eugene M. Shoemaker of the U.S. Geological Survey lead to estimates of the contributions that projectiles make today to the cratering of the Saturnian moons. For virtually any source of projectiles outside the Saturnian system the flux of impacts turns out to vary dramatically from the leading hemisphere to the trailing hemisphere of any given moon. For Dione, Shoemaker calculates a variation of 10 to one. For Rhea the variation is six to one. It makes no difference whether the projectiles are comets or asteroids or whether they have periodic orbits around the sun because the gravitational acceleration imparted to an arriving projectile by Saturn overwhelms the projectile's original trajectory.

Shoemaker further calculates that from the apex of Dione to the side of the body (with respect to the orbital motion of Dione around Saturn) the flux of arriving projectiles changes by a factor of

DIONE was photographed by *Voyager 1*. An image made on November 11, 1980 (*top*), shows the side of the moon that faces away from Saturn. The orange background is the top of Saturn's clouds, 377,000 kilometers from the moon. Dione is moving toward the right; the trailing hemisphere is at the left. The center of the trailing hemisphere shows bright wisps on a dark field. According to one hypothesis, a pattern of wisps once covered the entire surface of Dione. It was erased by the continual impact of small meteoroids over the history of the solar system, except at the center of the trailing hemisphere, where relatively few such projectiles arrive. An image made on November 12, 1980, at a range of 162,000 kilometers (*bottom*) shows what amounts to the prow of Dione. The apex of the leading hemisphere is at about the middle of the terminator along the left of the image. At the right is the side facing Saturn. The beginnings of several bright wisps in the trailing hemisphere are at the right limb of the moon.





LARGE IMPACT CRATER on Tethys is notably different from one on Mimas. The crater on Tethys (*left*) is more than 400 kilometers in diameter. It was photographed by *Voyager 2* at a range of 826,000 kilometers. When the crater was made, it must have been deep, and its rim and central peak must have been high. Today, however, the floor of the crater has rebounded to match the contour of the moon, and both the rim and the central peak have collapsed. Apparently Tethys once was warm enough to allow such rearrangement. In this image the apex of the leading hemisphere is near the center of the disk of the moon. The crater on Mimas (*right*) is 130 kilometers in diameter. It was photographed by *Voyager 1* at a range of 425,000 kilometers. It is the only large crater on Mimas. Its rim and its central peak are prominent. Apparently Mimas has long been cold. The crater's central peak lies at the apex of the leading hemisphere.

only two. From the side to the trailing end it changes by a factor of five. As a result the part of Dione least affected by the continuing impact of projectiles is only a small region at the trailing end of the moon.

With the aid of Shoemaker's calculations a history of Dione can be proposed. In this history the early life of Dione was dominated by the impact of large bodies most likely left over from the accretion of the solar system. Then parts of Dione were resurfaced. Meanwhile collisions near Saturn between the bodies left over from the accretion of the solar system yielded smaller bodies. Some of them took up orbits around Saturn much like Dione's. Their impacts with Dione cratered the newly formed plains moderately. At about this time fractures formed in the surface of Dione. The fractures were filled by bright extrusions from the interior.

It is likely that the entire surface of Dione then had the pattern now seen only at the center of the trailing hemisphere of the body. Over the past four billion years, however, Dione has rotated synchronously and its surface has been "gardened" by the impact of small meteoroids from outside the Saturnian system. The craters made by these bodies may be too small and too scattered to be identified in Voyager images. Still, the craters would rework the surface. In this way they erased the pattern of the surface in a region extending from the apex of the leading hemisphere well into the trailing hemisphere. This history accounts for the global pattern of albedo. The meteoroids arriving well into the history make up Population III.

Tethys

Tethys is the next moon inward from Dione; it travels in orbit around Saturn at a distance of 5 R_s. Its diameter is almost identical with that of Dione, but its density—1.2 grams per cubic centimeter—is lower. Moreover, its appearance is quite different. *Voyager 1* viewed Tethys only at low resolution. The images showed diffuse patches of small variation in albedo on a heavily cratered surface. The pattern did not resemble the more pronounced global pattern seen on Rhea and Dione. One of the best images showed a branching canyon spanning the distance between the north and south polar regions on the side of the moon facing Saturn. It was estimated the canyon was at least 1,000 kilometers long, 100 kilometers wide and several kilometers deep.

Nine months later *Voyager 2* approached Tethys. The images it transmitted to the earth revealed an enormous impact scar in the leading hemisphere. The rim of the scar has a diameter more than two-fifths the diameter of Tethys itself. As the spacecraft continued its approach the scar was photographed progressively closer to the visible edge of the moon. Soon an image showed it in profile. Here it could be seen that the floor of what must once have been a crater now matches the spherical shape of the body. Only a low rim and a subdued central peak remain. Evidently the interior of Tethys was sufficiently warm early in the history of the moon to allow the collapse of the raised topography. The same could be said of large craters on the icy Jovian moons Ganymede and Callisto.

Finally the north pole of Tethys and the side facing away from Saturn came into view. From this vantage it was apparent that the canyon found by *Voyager 1* extends over the north pole and down to the equator on the outward-facing hemisphere; thus the canyon traverses three-fourths of a great circle around the body. It could also be seen that parts of Tethys (like parts of Rhea and Dione) had been resurfaced. Smooth plains had developed in a small part of the leading hemisphere, and the resurfacing had buried some of the large craters already there.

A tentative explanation for the current appearance of Tethys begins with the surmise that at the time the large impact scar was made the interior of the body was much warmer and more mobile than it is today. Perhaps it was liquid. If Tethys had been cold and brittle when the scar formed, the impact that formed it might well have fragmented the moon. Moreover, the topography raised by the impact has clearly collapsed. The rim and the central peak of the impact scar persist. Hence it seems likely that much of the crust of Tethys in place at the time of the impact remains at the surface today. One can imagine, then, a simple history in which Tethys freezes from the crust down. If Tethys had first been liquid, the freezing would

have increased the volume of the object by about 10 percent and the surface area by about 7 percent. The estimated extent of the canyon on Tethys suggests that it forms 5 to 10 percent of the surface. The canyon may represent the stretching of Tethys' crust over the expanded, frozen interior.

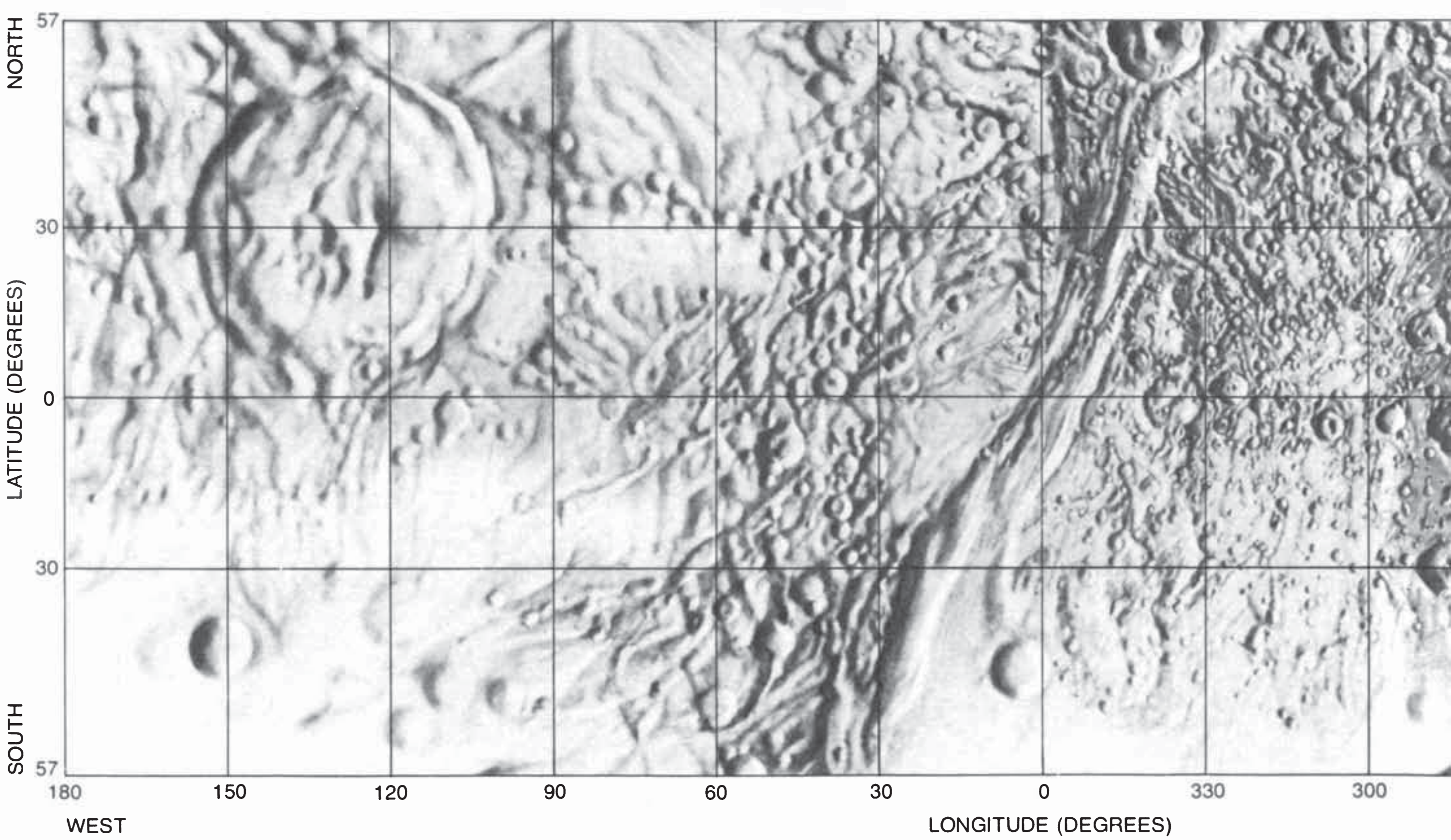
Mimas and Enceladus

The smallest of the nine moons whose presence around Saturn was known before the 20th century are Mimas and Enceladus. Each of them has only a thousandth the mass of a Galilean moon of Jupiter, a thousandth the mass of the earth's moon and a hundred-thousandth the mass of the earth. Their tininess is significant. Before the Voyager spacecraft began to explore the outer solar system the main source of heat in a planet or a moon was taken to be the decay of the radioactive atomic nuclei within it; hence it seemed that the history of a planet or a moon would be determined by the ratio of its volume to its surface area. The volume governs the quantity of radioactive nuclei and thus the generation of heat; the surface area governs the loss of heat and conversely the retention of it. The ratio of volume to surface area is determined by the size of the object: the ratio increases with the radius. One therefore supposes larger bodies are more likely to melt than small ones. Certainly the attribution of internal heat to radioactivity and the resulting correlation of heating with size explains the observations that volcanically the earth's moon is long dead, Mars is moderately active and the earth is quite active. It also suggests, however, that tiny moons such as Mimas and Enceladus should not have evolved substantially since the time they accreted.

The image of Mimas made by *Voyager 1* showed a surface that conforms to this prediction. The surface is uniform in albedo and is saturated with impact craters. It is a surface that has not been reworked by volcanism since the time of the Population I bombardment. In the leading hemisphere of Mimas there is an impact crater 130 kilometers in diameter, about a third the diameter of the little moon. One suspects other craters of that size or even larger should have been made in the course of the bombardment. Why are they not seen? If a cold, brittle Mimas had been blown apart by one such impact, the relative velocities at which the debris would fly apart would probably have been on the order of the velocity required for escape from Mimas' gravity. Such velocities are small compared with the orbital speed of Mimas, which is 30 kilometers per second. Hence the debris would have remained in a narrow band surrounding what had been the orbit of the moon. Gradually the debris would have reaccreted. The result would have been a cold mass of rubble consisting mostly of ice, but with a few percent of rock. (The density of Mimas is 1.2 grams per cubic centimeter.)

The statistics of the craters seen on Mimas suggest this may have happened. On Mimas today the largest crater is the one 130 kilometers in diameter. Then comes a gap in the sizes. The next-largest craters have diameters of only a few tens of kilometers. After that the abundance of craters increases exponentially as the diameter of the craters decreases. It is as if a large-scale impact had destroyed a parent body and the fragments had recombined. The present pattern of craters results, then, from impacts by the last of the fragments. The single largest crater represents a collision not energetic enough to have destroyed the body again; the other large craters made by Population I objects disappeared with the disruption of the parent body.

Voyager 1 provided only distant views of Enceladus, yet if the craters on Enceladus resembled those on Mimas, the im-

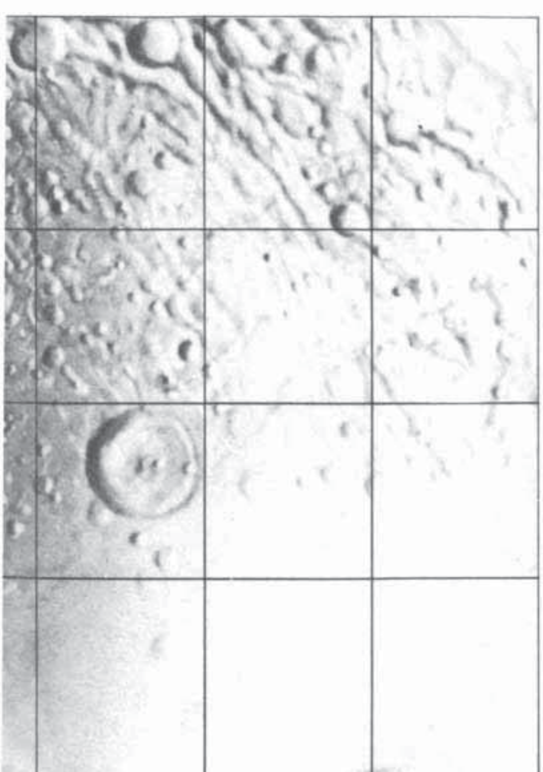


MAP OF TETHYS was prepared by the U.S. Geological Survey from images made by *Voyager 1* and *Voyager 2;* it is a Mercator projection, in which all latitudes and longitudes are made rectilinear. Zero degrees of longitude marks the center of the side of the moon that faces Saturn, 90 degrees marks the center of the leading hemisphere and 270 degrees marks the center of the trailing hemisphere. Two features dominate the topography. One of them is the collapsed impact crater shown in the photograph at the left on page 110. The central peak of the crater lies near 120 degrees longitude and 30 degrees north latitude. The other feature is a great canyon running from south to north between 30 and 330 degrees longitude. The canyon extends over the north pole of Tethys and then back toward the

ages should have shown them. A crater as large as the one in the leading hemisphere of Mimas should certainly have been visible. Instead the images showed a surface that seemed to be smooth. More important, the surface of Enceladus was brighter than that of the neighboring moons Mimas and Tethys. This suggested that much of the surface of Enceladus may have been regenerated and is covered with very fresh ice.

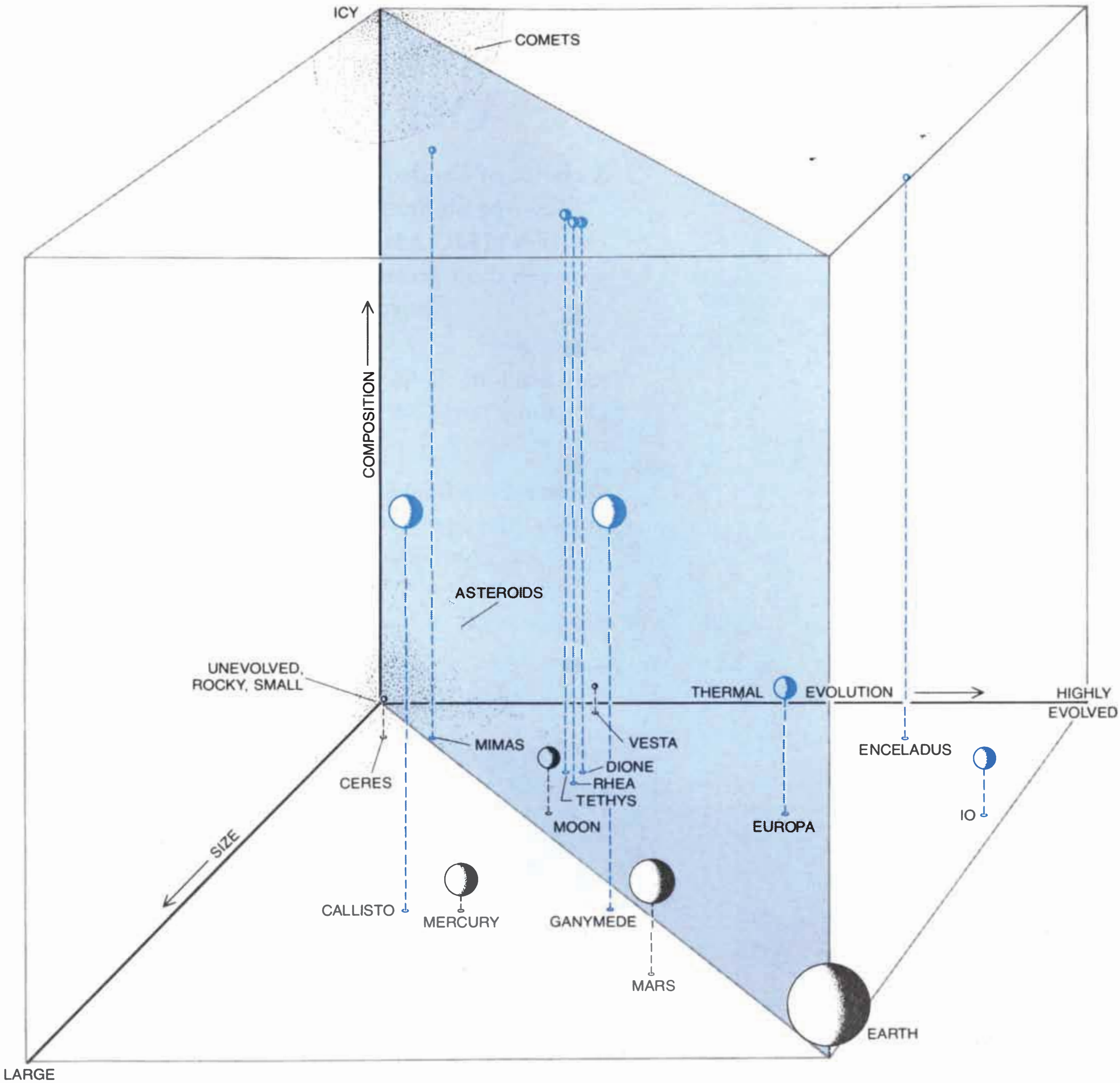
Two chains of reasoning had already implied that Enceladus was unusual. In the first place observations made from the earth had shown that the diffuse ring of Saturn designated the *E* ring has its maximum brightness along the orbit of Enceladus. This suggested that Enceladus might be the source of the ring. Indeed, it suggested that Enceladus might continually replenish the ring, because otherwise the gravitational field of the moon would tend to clear matter out of its orbit. (It is proposed that such gravitational shepherding is responsible for at least some of the banding discovered by the Voyager spacecraft in the rings of Saturn.)

In the second place, an argument developed by Stanton J. Peale of the University of California at Santa Barbara and his colleagues had led to the conclusion that Io, the innermost major moon



equator; its end is apparent at the upper right of the map. The canyon may represent the stretching of the crust of Tethys over an interior that expanded as it cooled and solidified into ice. The terrain on the map is shown as though it were all illuminated from the west.

of Jupiter, is heated substantially by tidal forces. Then Charles F. Yoder of the Jet Propulsion Laboratory of the California Institute of Technology proposed that a similar mechanism might act on Enceladus. Specifically, the orbital period of Enceladus is half that of Dione. This means that Enceladus and Dione align themselves with Saturn at fixed points in their orbits. The gravitational attraction of Dione for Enceladus acts repeatedly at these points, so that although the attraction is small, it makes the orbit of Enceladus stay slightly elliptical. In such an orbit Enceladus is forced to oscillate radially in Saturn's gravitational field, much as Io oscillates radially in Jupiter's. The internal friction that results from this oscillation might keep the interior of Enceladus warm and mobile. Gases and fluids es-



WIDE RANGE OF HISTORIES among planets and moons in the solar system is suggested when planets and moons with a visible solid surface are plotted in a cube whose axes represent their composition (from rocky bodies at the bottom of the cube to icy bodies at the top), their thermal evolution (from cold, unevolved bodies at the left to highly evolved, volcanic bodies at the right) and their size (from small bodies at the back to large bodies at the front). The black spheres are bodies whose position could be plotted before the Voyager spacecraft arrived in the outer solar system. In general these bodies (including Mercury, the earth, the earth's moon and Mars) are rocky. Moreover, the larger they are, the more they show signs of evolution and recent volcanic activity. In the illustration the rocky composition of the bodies means they lie near the bottom of the cube; the correlation between their size and their thermal evolution means they lie near a plane that passes through the cube diagonally from left to right. The correlation between size and evolution implies they derive their internal heat primarily from the decay of radioactive atomic nuclei. The colored spheres represent bodies that can be placed in the cube as a result of the study of their solid surface in Voyager images. Such bodies occupy a large part of the volume of the cube. They include Io and Enceladus, two small but highly evolved bodies that are thought to derive their heat from internal friction as each one moves in a slightly elliptical orbit around its parent planet. Io is a rocky moon, Enceladus is icy. Io, Europa, Ganymede and Callisto are the four major moons of Jupiter discovered by Galileo; Ceres and Vesta are bodies in the asteroid belt between the orbits of Mars and Jupiter.

caping from the interior might then keep the surface bright and remove the traces of craters. Allan F. Cook II of the Harvard College Observatory and the Smithsonian Astrophysical Observatory and Richard J. Terrile of the Jet Propulsion Laboratory have proposed that if Enceladus is geologically active, gases escaping from the interior of Enceladus and ice particles escaping from the surface might be the source of the *E* ring's material.

As *Voyager 2* flew close to Enceladus last August it transmitted back to the earth images that showed some craters after all. The craters, however, are sparser than the ones on Mimas, and some of them are in a state of collapse similar to that of old craters on Jupiter's moon Ganymede. The images of Enceladus made at the highest resolution show plains marked by a network of braided ridges but no craters whatever down to the limit of resolution. How old could such a surface be? Shoemaker's calculations suggest that the comets currently traversing the outer solar system should make craters on the plains that are visible at the resolution of the Voyager images in a few hundred million years. That amounts to about 10 percent of the age of the solar system. If other unseen bodies also hit Enceladus, the plains must be even younger.

It seems unlikely that Enceladus has been geologically active for 90 percent of its age but has now become inert; it is therefore highly likely that Enceladus is active today. The *E* ring and the extremely high albedo of the surface may result from this activity. It should be added that estimates of the effectiveness of tidal heating in Enceladus suggest that the amount of energy supplied by tidal forces is too small and too easily radiated into space for the interior to be a liquid if it consists of water. Perhaps, however, the interior includes methane clathrates or hydrates of ammonia. Such substances have a melting point about 100 degrees Celsius below that of pure water ice.

At least six different types of terrain can be distinguished on the surface of Enceladus. The oldest two are cratered terrains designated *CT*1 and *CT*2. They show a population of craters 10 to 30 kilometers in diameter that almost certainly date back to a period of Population II bombardment in which Enceladus was hit by debris in orbit around Saturn. On the *CT*1 terrains most of the craters have collapsed: their floors have rebounded, their rims have sunk and their central peaks are better described as gentle domes. On the *CT*2 terrains the craters are deep and bowl-shaped. The difference suggests that these different parts of Enceladus have had different thermal histories. The *CP*1 terrains are plains that show a relatively sparse distribution of craters between two and five kilometers in diameter. The craters lie on a rectilinear pattern of faults. Shoemaker's calculations suggest a range of ages. If the flux of recent projectiles has been minimal, the *CP*1 terrains may date back to nearly the time of the Population II bombardment more than four billion years ago. If the flux has been substantially greater, they may be a billion or even two billion years younger. In any event three still more recent terrains (*CP*2, *CP*3 and *RP*) also formed on Enceladus. They are revealed by the presence of corridors that cut through the older terrains so that parts of craters are obliterated.

The *RP* terrain includes the plains that show no craters. Its margin is marked by braided ridges. Two tentative hypotheses have been offered for the origin of the ridges. One explanation is that a system of faults was invaded by liquid water that froze. The expansion of the ice is what raised the topography. The other explanation is that a zone of solid-state convection slowly makes matter rise in the center of the plain and sink elsewhere, producing a roughly concentric pattern of wrinkles. Clearly Enceladus joins Io in showing that radioactivity does not always dominate the heating of bodies in the solar system. Enceladus has a hundred-thousandth the mass of the earth. It may nonetheless be just as active geologically.

Different Evolutions

The exploration of the Jovian and the Saturnian systems of moons by the Voyager spacecraft has yielded new insights into the evolution of the small bodies in the solar system. Imagine a three-dimensional chart whose axes are determined by measures of a body's size, composition and thermal evolution. Before the Voyager missions the only bodies that could have appeared in such a chart would have been the planets, moons and asteroids of the inner solar system. All of them fall into essentially the same class of objects of rocky composition, and their degree of thermal evolution is closely related to their size—a correlation suggesting that radioactive heating has dominated their history. In the wake of the Voyager missions a large part of the chart gains occupants, and the simple trend of evolution with size is destroyed.

Much remains to be discovered about the evolution of the moons in the solar system, but already it is apparent that nonradioactive sources of energy (for example tidal heating) are important for some of them. Moreover, it is apparent that an icy composition can allow vigorous geological activity even in very small moons. Further studies of moons will surely tell us much about both the conditions and processes in the incipient solar system and the ways planets evolve under a wide variety of circumstances.