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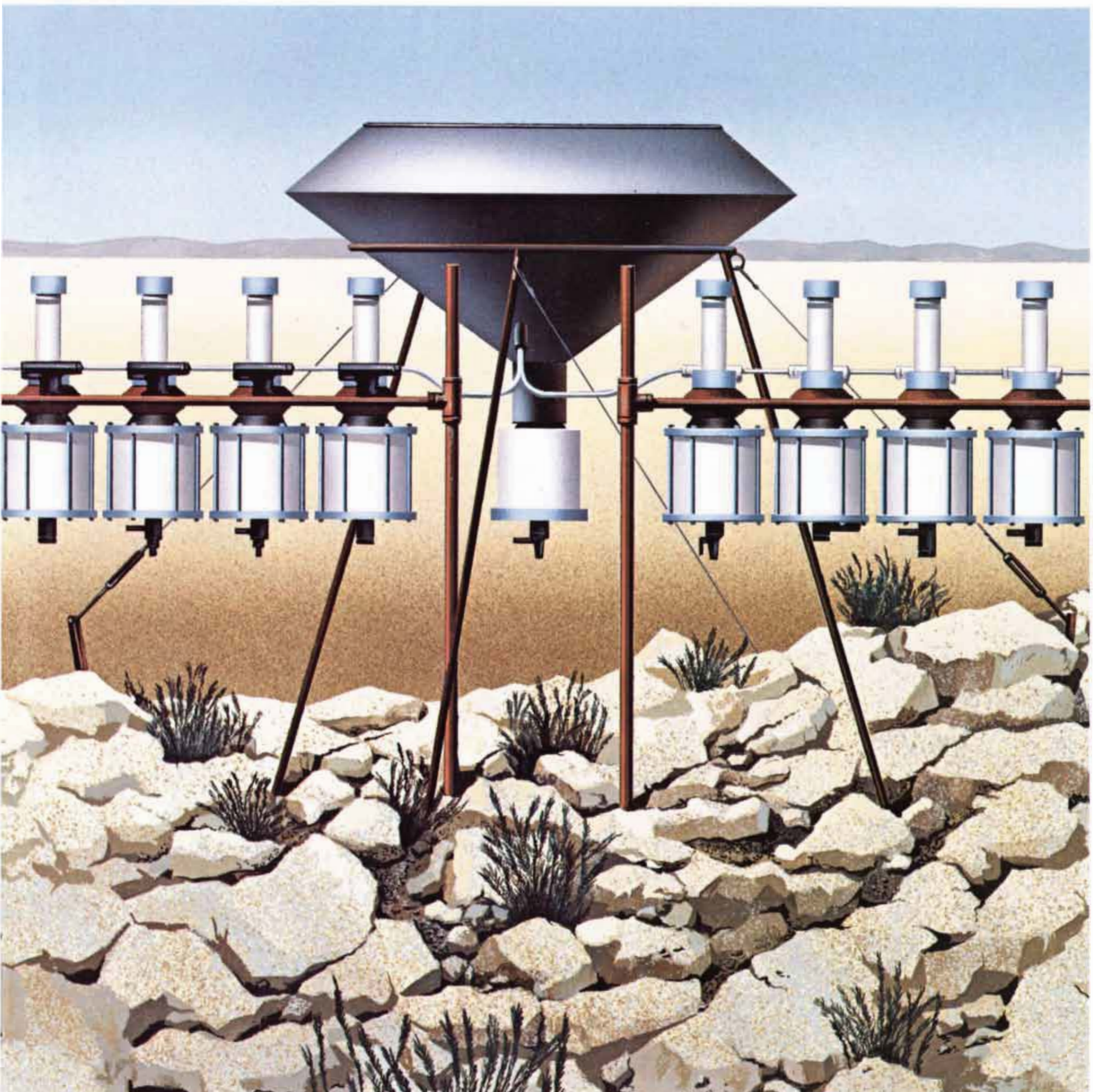

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The Moons of Uranus, Neptune and Pluto

When Voyager 2 flies by Uranus in January and by Neptune in 1989, it will send back closeup pictures of their icy moons. Ground-based studies of the outer solar system suggest what the probe might find

by Robert Hamilton Brown and Dale P. Cruikshank

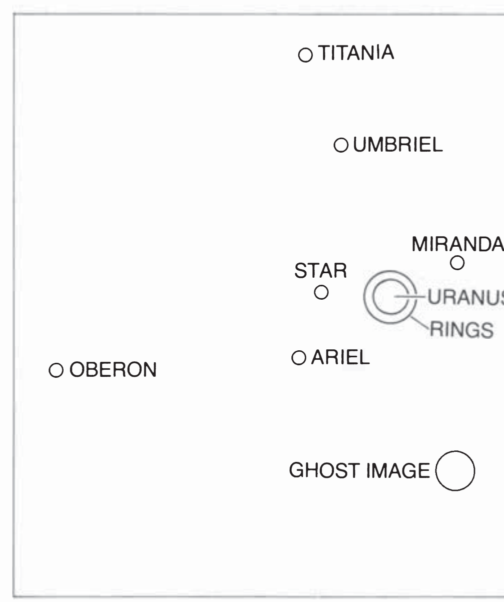
Just over 200 years ago an observation by an amateur astronomer doubled the size of the known solar system. Peering through a homemade six-inch telescope, William Herschel discovered Uranus, the seventh planet. Sixty-five years later Neptune was recognized; like Uranus, it is a giant planet roughly four times the size of the earth. Pluto, no larger than the earth's moon and twice as far as Uranus from the sun, did not emerge from the black until 1930. By that time, thanks to enterprising astronomers and rapidly improving astronomical instruments, it had become apparent that the outer three planets do not travel alone. Uranus was eventually found to have at least five moons and Neptune at least two. In 1978 Pluto's first satellite was detected on a grainy photograph of the planet.

Until recently little was known about the satellites of Uranus, Neptune and Pluto other than the parameters of their orbits. In contrast, the Pioneer and Voyager spacecraft had sent back stunning images and a wealth of data on the satellites of Jupiter and Saturn, transforming those remote specks into worlds whose history could be discerned, if only in outline. A similar era of discovery is about to begin for Uranus and Neptune. *Voyager 2,* launched in August, 1977, will fly by Uranus next January, passing within 29,000 kilometers of the planet's innermost moon, Miranda. The spacecraft will then encounter Neptune in August, 1989, on its last rendezvous before leaving the solar system. Unconstrained by the need to steer the probe toward another destination, the mission planners are taking full advantage of the final encounter. *Voyager 2* will fly within 10,000 kilometers of Neptune's inner satellite, Triton. Images of Triton made by a high-resolution camera are expected to reveal surface features as small as a few hundred meters in diameter.

In preparation for the Voyager flybys the pace of ground-based investigations of the moons of Uranus and Neptune has quickened considerably. The same is true of Pluto, which in some ways is more like a satellite than a planet, and of its moon, Charon. The increased interest, together with a vast improvement in telescopic detector technology, has begun to yield an understanding of the physical properties of these bodies. What follows, then, is a preview—a somewhat indistinct first look at objects that promise to be among the most interesting in the solar system.

With ground-based telescopes one can learn a number of important things about remote planetary satellites. First, one can determine the shape, size and period of their orbits and thereby make accurate predictions of their positions. More important, knowledge of a satellite's orbital parameters enables workers to calculate the mass of the planet and the strength of its gravitational field at various locations. The mass of the satellite itself can often be inferred by observing the perturbations it induces in the orbits of other satellites. If its diameter is known, one can then compute its mean density, which is the most important clue to bulk composition.

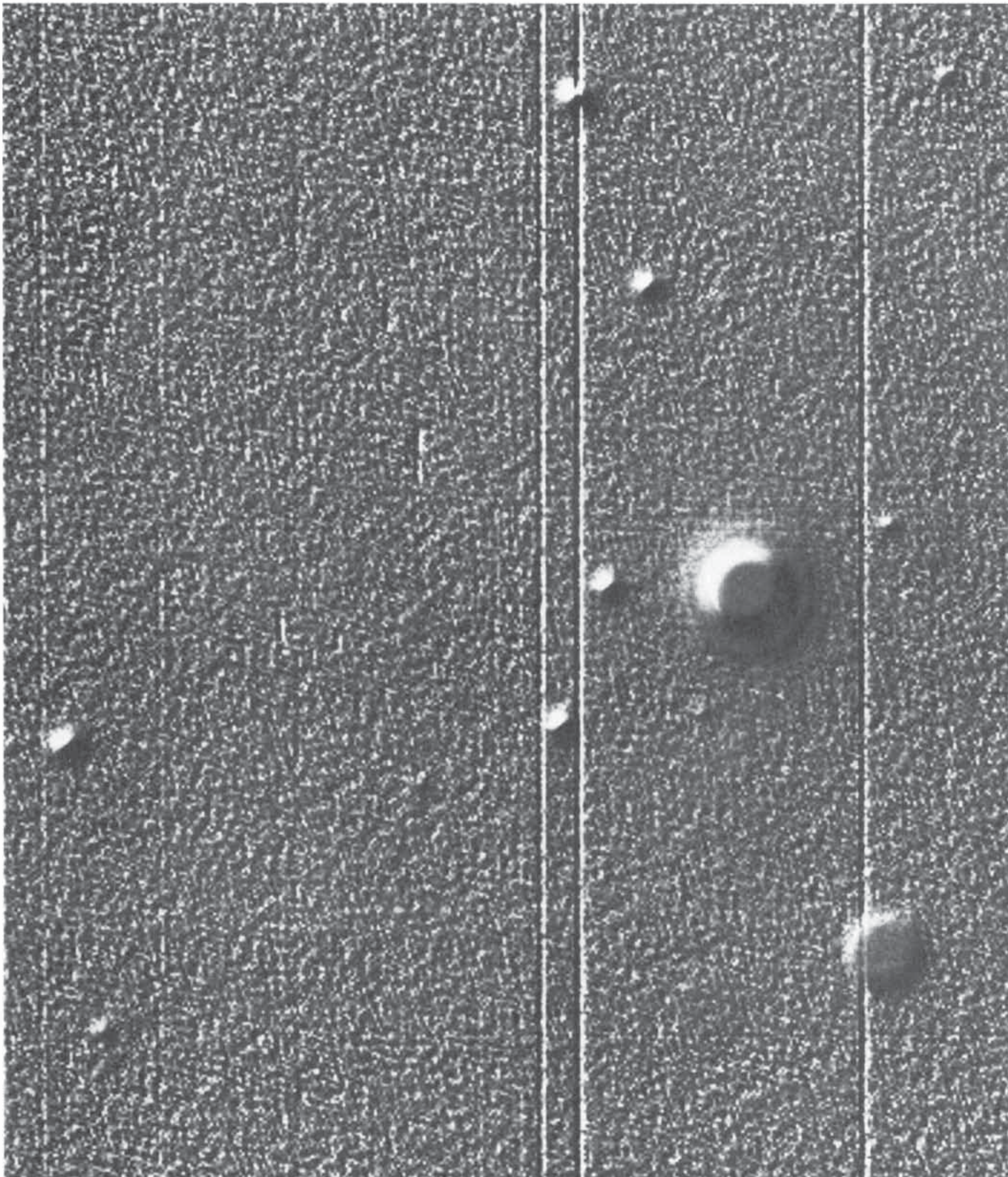
Information on surface composition can be gleaned more directly from absorption bands in the spectrum of sunlight reflected off the satellite. By comparing the observed spectrum with the laboratory spectra of various chemical elements or compounds one can identify some of the satellite's surface constituents. This work is best done in the near-infrared region (at wavelengths of one micrometer to five micrometers), because most of the molecular substances common in the solar system have strong absorption signatures in that range. Even when it is observed through the largest telescopes, however, the radiation from small, distant satellites is extraordinarily faint. Not until the late 1970's were infrared detectors capable of resolving it into

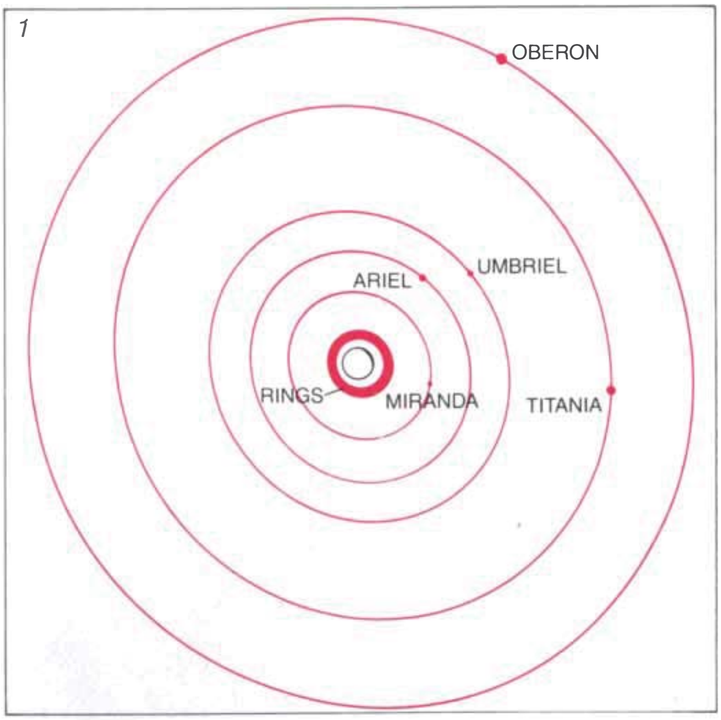


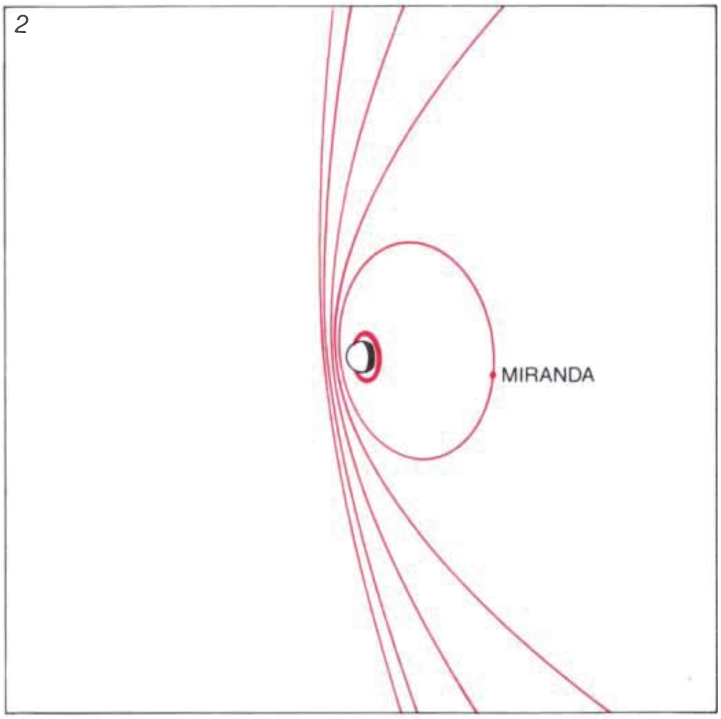
FIVE MOONS OF URANUS are seen on an electronic image made by Bradford A. Smith of the University of Arizona and Richard J. Terrile of the Jet Propulsion Laboratory. The visible-light image, produced with a charged-coupled device attached to the Carnegie Institution of Washington's 2.5-meter telescope in Chile, also shows the planet's thin rings of dark particles. Uranus' spin axis lies almost in its orbital plane; at present its south pole is pointed toward the earth and the sun. The orbit of Miranda, the innermost moon, is inclined by several degrees, but the other moons orbit Uranus in its equatorial plane. The vertical lines are caused by defects in the electronic detector.

spectra. (The new detectors use indium antimonide rather than lead sulfide as the light-sensitive compound; infrared radiation produces free electrons in the indium antimonide, generating an electric current whose intensity is proportional to that of the radiation.)

Theories of how the solar system evolved give some idea of what to expect in investigating the composition of bodies in its outer regions. The formation of both satellites and planets is thought to have begun with the accretion of frozen dust grains that condensed out of the primitive solar nebula as it cooled. The composition of the grains and hence of the larger bodies depends on their distance from the sun. In the hot region near the sun only relatively refractory substances could condense. As a result the inner planets—







PASSAGE OF *VOYAGER 2* through the Uranian system will offer a close look at the planet and at Miranda. The drawings, adapted from computer simulations prepared by mission planners at the Jet Propulsion Laboratory, show views through the spacecraft's cameras from several points on its trajectory. *Voyager 2* is approaching the sunlit south pole of Uranus at a speed of about 53,000 kilometers per hour. Ten days before its closest approach to the planet on January 24, 1986, the probe's wide-angle camera will still

Mercury, Venus, the earth and Mars—are rocky bodies consisting primarily of metals, metal oxides and silicates. At the distance of Jupiter the solar nebula cooled to temperatures low enough for ices to form; water ice seems to make up a significant part of the Jovian satellites and the bulk of Saturn's moons. Still farther from the sun, in the range of Uranus, Neptune and Pluto, one would expect to find water ice, but also ices of materials even more volatile than water: methane (CH_4) and ammonia (NH_3).

Uranus and its five moons—beginning with the outermost they are Oberon, Titania, Umbriel, Ariel and Miranda—make up the third-largest satellite system after the Jovian and Saturnian systems. The smallest of the group, Miranda, is six times fainter than the faintest of the others. It was discovered in 1948, and since then no new Uranian satellites have been observed in spite of concerted efforts with the largest telescopes and the most sensitive detectors. *Voyager 2* will undertake a special search. If experience with Jupiter and Saturn is a guide, the search may well reveal tiny moons that have escaped detection from the earth.

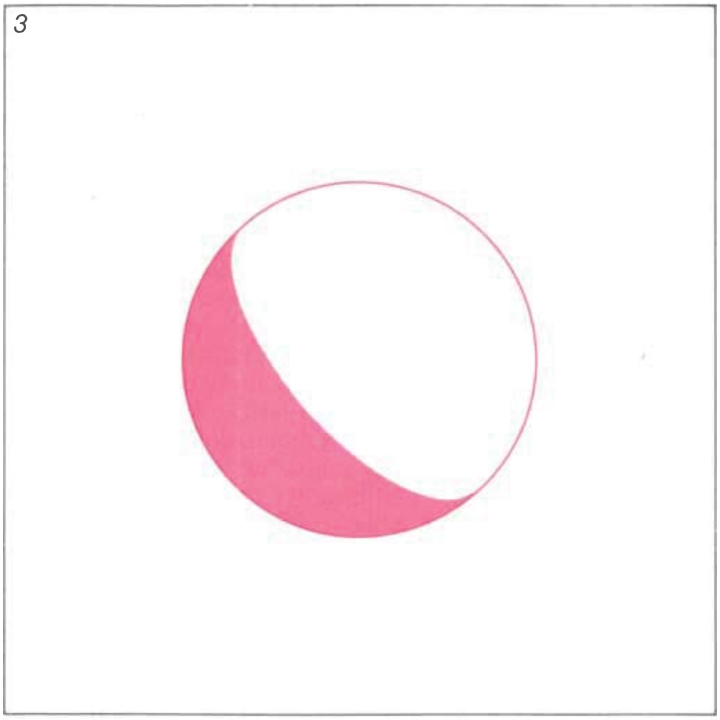
The known Uranian satellites travel in virtually circular orbits, and except for Miranda their orbital planes coincide with the planet's equatorial plane to within a few tenths of a degree. Although the satellite orbits are quite regular, the orientation of the entire system is unusual: it is tilted on its side, so that the rotation axes of both the planet and its moons lie nearly in the planet's orbital plane. Some workers attribute Uranus' odd orientation—as well as the less extreme inclinations of other planetary axes—to the impact of a planetesimal early in the planet's history. It has been suggested that such a catastrophe would have affected the evolution of the Uranian satellites, but so far there is no strong evidence to support or refute this hypothesis.

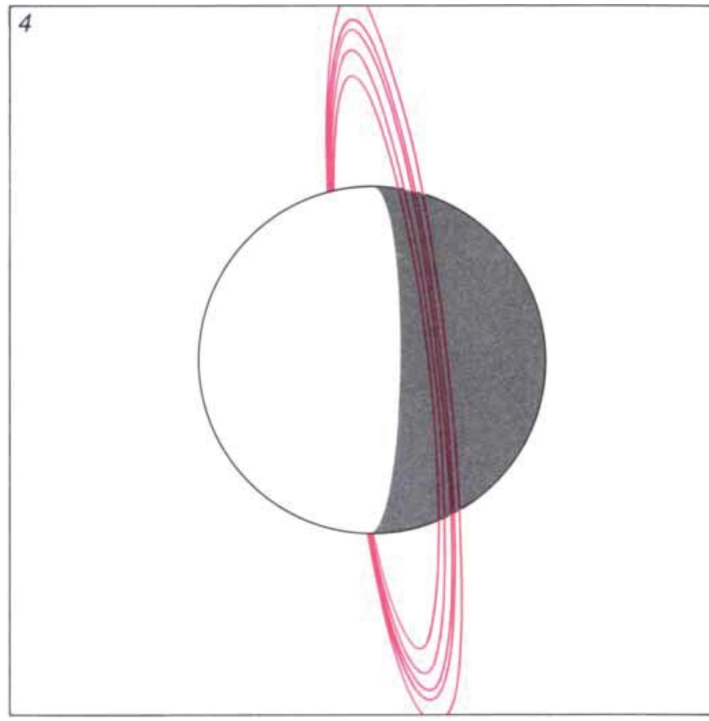
In 1979, even before the size and mass of the Uranian moons could be determined with confidence, we established the presence of water ice on the surface of the four outer ones. The near-infrared spectra we measured with the four-meter telescope at the Kitt Peak National Observatory all displayed the characteristic signature of water ice: broad, strong absorption bands at wavelengths of 1.5 and 2.0 micrometers. In 1983 one of us (Brown) and Roger N. Clark of the U.S. Geological Survey resolved the spectrum of Miranda for the first time; the data are relatively crude, but they show the 2.0-micrometer absorption band fairly clearly.

By then B. Thomas Soifer and his colleagues at the California Institute of Technology had confirmed our earlier results. Furthermore, their spectra suggested the presence of an additional compound on the surface of the Uranian satellites. Although the investigators were not able to identify the new component, they concluded it was significantly darker than water ice.

In the course of measuring the diameter of the Uranian moons we verified that their reflectivities are indeed lower than would be expected if they were composed of pure, pulverized water ice. The connection between diameter and reflectivity is worth explaining in detail. Because the Uranian satellites are so distant, the diameter of the disks they present to observers on the earth cannot be measured directly. At the same time the measurable intensity of their reflected light does not offer unambiguous information on their size: a satellite of a given brightness might be small and highly reflective or large and comparatively dark.

The ambiguity can be resolved by measuring the satellite's thermal flux, which also depends on its size and reflectivity. Sunlight that is not reflected heats the surface of the satellite and is reradiated as thermal energy at longer, infrared wavelengths (between 20 and 100 micrometers in the case of the Uranian moons). By combining radiometric measurements of the infrared heat flux with photometric measurements of brightness, one can in principle construct and solve a system of two equations in which the two unknowns





take in the entire satellite system (*1*). Two hours before the closest approach (*2*) the spacecraft will be nearing Uranus' equatorial plane between the orbits of Miranda and Ariel. As it passes within 29,000 kilometers of Miranda an hour later, its high-resolution camera will make images (*3*) that may reveal evidence of volcanic activity, such as geologically recent ice flows. About 13 minutes after that, as *Voyager 2* crosses the equatorial plane, high-resolution images will show the dark side of Uranus and the edge of its rings (*4*).

are the satellite's diameter and reflectivity. (In practice one must also make certain assumptions about the satellite's radiative properties. Fortunately these turn out to be quite simple for a surface consisting of fine ice grains loosely aggregated in a vacuum, because such a surface does not store or conduct much heat.)

Measuring the diameters of the Uranian satellites by means of the photometric-radiometric technique has nonetheless proved difficult. The surface temperature of the satellites is only 80 degrees Kelvin (degrees Celsius above absolute zero), and Uranus is never closer than about 2.7 billion kilometers from the earth. Furthermore, water vapor in the earth's atmosphere absorbs much of the incident infrared radiation. As a result the thermal flux from the Uranian moons is barely detectable even with the best infrared telescopes; indeed, Miranda's is not detectable at all.

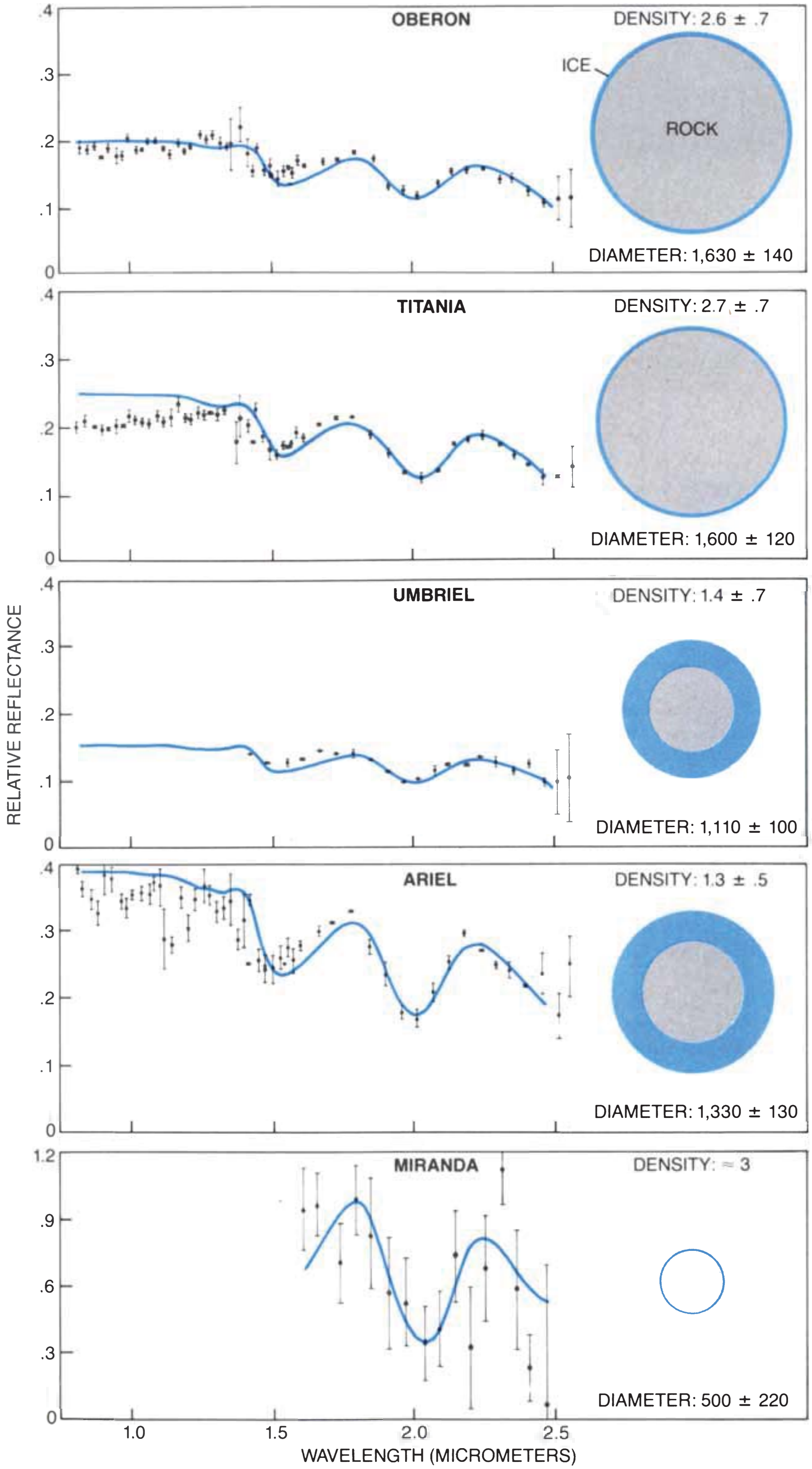
One of the best infrared telescopes is the National Aeronautics and Space Administration's facility on the Hawaiian peak Mauna Kea, which at an altitude of 4,200 meters benefits from a relatively dry atmosphere. Working there in 1981 with David Morrison of the University of Hawaii at Manoa, we measured the thermal flux and calculated the diameter and reflectivity of the outer four Uranian moons. We found they are much larger and darker than had been thought when it was assumed that their surfaces were pure water ice. Although they are considerably smaller than the four Galilean moons of Jupiter, Saturn's Titan and the earth's moon, they are among the largest satellites in the solar system.

What, then, is the substance that darkens their surface? At first we were puzzled by the absence, even on more recent high-resolution spectra, of absorption bands other than those attributable to water ice. Soon a possible explanation suggested itself: the dark substance might be spectrally neutral. In other words, it might be a colorless material that reflects very little light and absorbs all wavelengths more or less equally.

In laboratory experiments we found we could approximately match the satellite spectra with the spectra of fine-grained water ice, or frost, covered with isolated, uniformly distributed patches of charcoal. The satellites differ in reflectivity, and correspondingly the surface models that best reproduce the individual spectra differ in their proportions of water ice and charcoal. Charcoal is merely a convenient laboratory material; since it is derived from living organisms, it is probably not found on the Uranian moons. Like charcoal, however, the dark substance on the satellite surfaces is likely to be spectrally neutral and to reflect between 5 and 15 percent of incident light. Materials fitting this description include a magnetic oxide of iron called magnetite, several silicate minerals and a dark organic polymer found in primitive carbonaceous meteorites.

Yet there is reason to believe such rocky materials might not account for the dark patches on the Uranian moons. Theoretical work by David J. Stevenson of Caltech suggests the moons are large enough to have undergone physical differentiation. During this process heat from the decay of radioactive elements in the rocks would have melted the interior of the moons, allowing rocky material to settle to the core. (Most smaller satellites, it is generally thought, do not undergo differentiation because heat escapes from their interior before it can induce melting.) Moreover, according to Stevenson, the melting might have been accompanied by extensive volcanic activity. Water ejected in volcanic eruptions would have covered the surface with a layer of nearly pure, fine-grained ice, burying any remaining exposed rocks.

Steven W. Squyres, now at NASA's Ames Research Center, and Carl Sagan of Cornell University have proposed an explanation for the origin of the dark material that may be consistent with both differentiation and volcanic resurfacing. According to their hypothesis, ultraviolet light from the



COMPOSITION OF URANIAN MOONS can be inferred from their near-infrared reflectance spectra and from their mean densities. The spectra of the four outer moons all have deep absorption bands at wavelengths of 1.5 and 2.0 micrometers, both of which are characteristic of water ice. The data for Miranda are crude (the vertical lines show the error range) but a strong absorption band is evident at 2.0 micrometers. The satellite spectra (*dots*) are matched closely by the spectra of two-component laboratory models (*lines*) consisting of water frost and charcoal. All the moons are thought to have an icy surface and a rocky core, but the differences in mean density (measured in grams per cubic centimeter) suggest that Ariel and Umbriel have thicker ice layers than Titania and Oberon. Miranda's density is too uncertain to allow a conclusion about its internal structure. The diameters are given in kilometers. In comparison, the earth's moon has a diameter of 3,480 kilometers.

sun decomposes methane trapped in water-ice crystals at the surface of the satellites. The resulting atomic carbon and hydrogen recombine with methane to form complex hydrocarbon polymers whose color is a dark red. Laboratory experiments by a number of workers have confirmed that methane ice or methane-contaminated water ice does indeed form dark organic polymers—similar to those found in carbonaceous meteorites—when it is subjected to energetic radiation. The radiation need not be ultraviolet light: the ice can also be darkened by gamma rays like those emanating from the center of the galaxy or by energetic charged particles like those found in the Van Allen belts formed by the earth's magnetic field.

If much of the methane on the surface of the Uranian moons has been converted into dark matter, that would explain why methane has not yet been observed there even though most models of solar-system formation predict its presence. It is also possible that the strong absorption bands of water ice mask the spectral signatures of methane as well as of ammonia. Unfortunately *Voyager 2* is not carrying any instruments designed to gather detailed data on the surface composition of the satellites. Images transmitted by the probe will yield some new information, but conclusive evidence of methane and ammonia, and of the identity of the dark surface constituent, will have to be obtained through improved ground-based observations or by future spacecraft. Whatever the dark substance is, small particles of it may also make up Uranus' nine narrow rings: the rings too are spectrally neutral, and their reflectivity is even lower than that of the dark patches on the moons.

In trying to understand the origin and evolution of the Uranian satellites information on their bulk composition is even more important than knowledge of their surface properties. The most revealing indicator of an astronomical object's bulk composition is its mean density, which can be calculated if its mass and diameter are known. Christian Veillet of the Centre d'Études et de Recherches Géodynamiques et Astronomiques in Grasse, France, recently made the first reliable calculations of the masses of the Uranian moons by refining previous measurements of their orbits.

Using our measurements of the diameters of the outer four satellites, Veillet found that Ariel and Umbriel respectively have densities of approximately 1.3 and 1.4 grams per cubic centimeter, whereas the densities of

Titania and Oberon are roughly twice as large. (The comparable figure for the earth is 5.5 grams per cubic centimeter.) Ariel and Umbriel are about as dense as many of the icy satellites of Saturn, and so their bulk composition may be similar. A mixture consisting of 55 percent by weight of water ice, whose mean density is 0.9 grams per cubic centimeter, and 45 percent rocky material with a density of 3.0 yields the correct overall density value. By the same reasoning Titania and Oberon consist of a mixture of 95 percent rock and 5 percent ice. Assuming that melting has caused the rock to settle into the core, the outer two Uranian moons would be rocky spheres with thin skins of water ice; Ariel and Umbriel would have much thicker ice layers and smaller rocky cores.

This conclusion, if true, is somewhat surprising. If the moons formed at the same time as Uranus itself, then heat released by the accretion of interstellar grains and the gravitational contraction of the protoplanet should have resulted in a larger amount of heavy material condensing near the planet. Ariel and Umbriel should therefore have a higher proportion of rock and a lower proportion of volatiles than Titania and Oberon. Veillet's contrary finding could be taken as evidence for the hypothesis, advanced by some workers, that the Uranian satellites were actually formed later, by the same catastrophic impact that supposedly knocked the planet on its side. Current models of the satellites' internal structure must be treated skeptically, however, because the density calculations on which they are based contain large uncertainties.

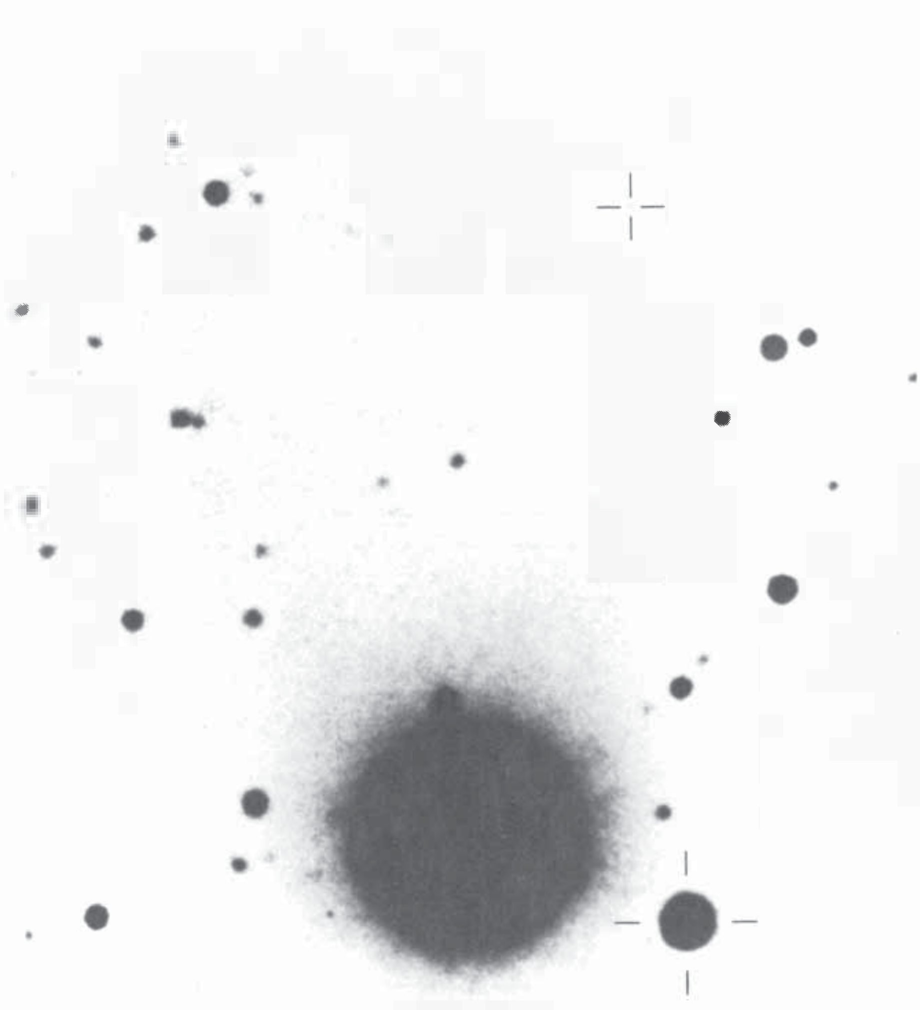
The greatest source of uncertainty is the diameter measurements, and so the situation should improve substantially when *Voyager 2* arrives at Uranus in January. Images transmitted by its high-resolution camera will enable workers to determine the diameter of all five satellites with high accuracy. Small deviations in the spacecraft's trajectory caused by the gravitational pull of Miranda will also make it possible to calculate that moon's mass with greater precision.

Just as important, the Voyager cameras will show what the satellites look like. The spacecraft will pass within 29,000 kilometers of Miranda and 127,000 kilometers of Ariel. The images of these two moons should reveal surface features as small as two kilometers wide. The angle of the probe's approach and its high velocity—about 10 times that of a rifle bullet—will allow only a small fraction of the satellite surfaces to be viewed in detail. Nevertheless, the images will probably show patches of light and dark material. They should also give an indication of the extent to which the Uranian satellites have been cratered by meteorites and resurfaced by fresh ice from below the surface.

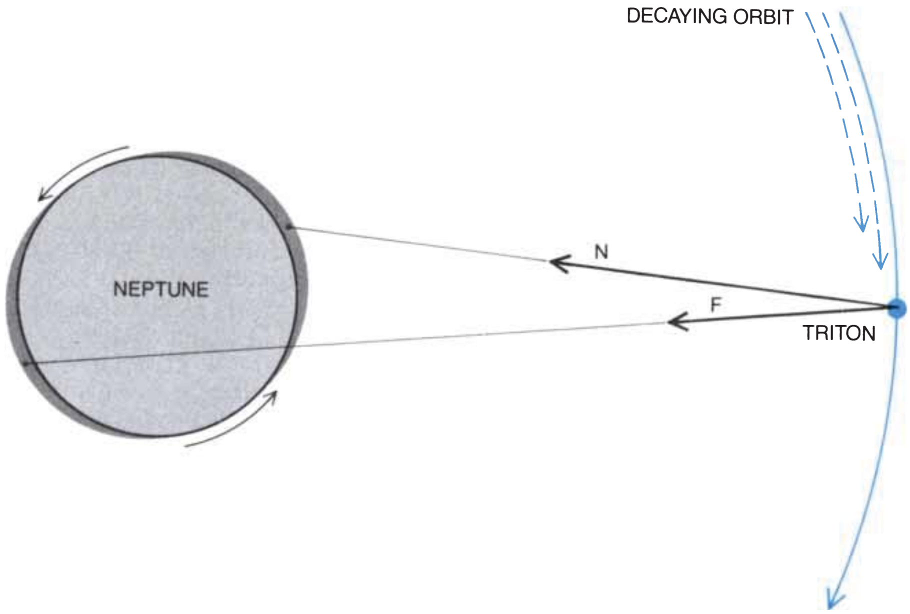
Theoretical studies suggest that volcanic activity and resurfacing may have occurred in the geologically recent past on Ariel and Miranda. Both are significantly more reflective than their companions, indicating they may be covered with extensive deposits of relatively fresh, undarkened ice. The Voyager images may reveal volcanic ice flows. If we are lucky, they may even record eruptions in progress, as they did on Jupiter's moon Io.

Three and a half years and more than a billion and a half kilometers later *Voyager 2* will encounter Neptune and its large satellite Triton. The spacecraft will not fly close to Nereid, Neptune's other moon, which is in a highly inclined elliptical orbit that takes it more than nine million kilometers from the planet. Almost nothing is known of Nereid's physical properties because it is very faint; from its luminosity it is judged to be between 150 and 525 kilometers in diameter, comparable to the largest asteroids.

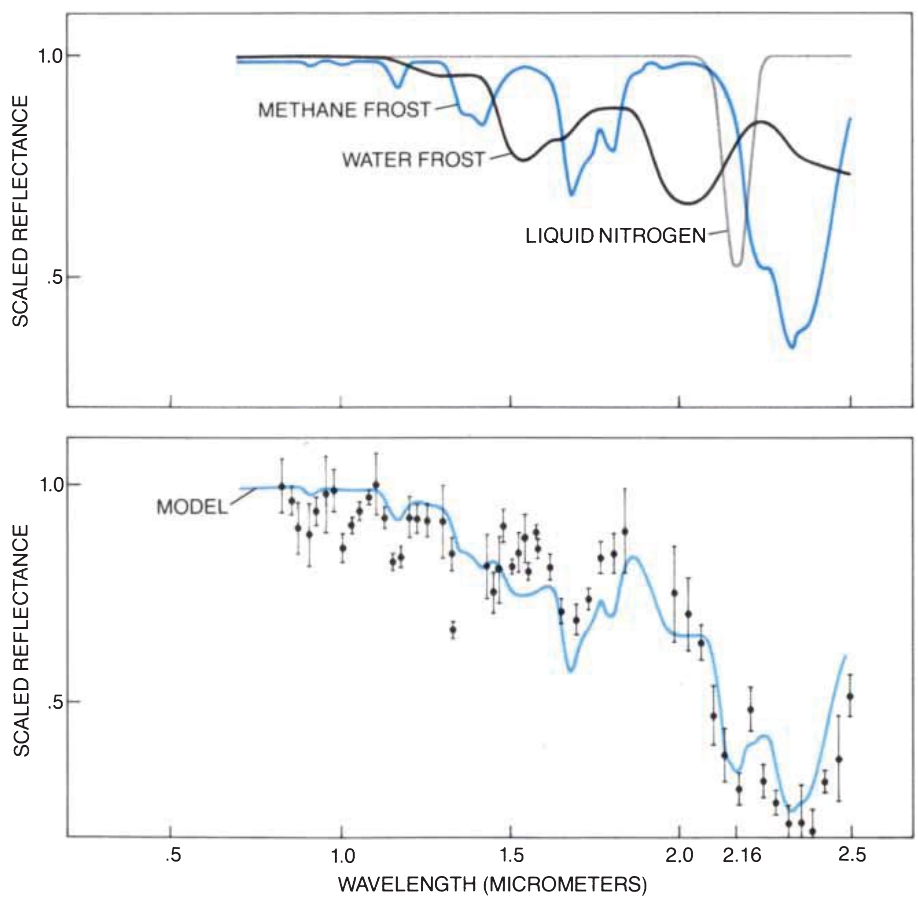
Triton, in a circular orbit roughly 350,000 kilometers from Neptune, is comparable in size to the earth's moon, which has a diameter of 3,480 kilometers. Triton's orbit is nearly coincident with the orbital plane of Neptune and is inclined by about 28 degrees to Neptune's equatorial plane. It is retrograde: the satellite revolves around Neptune in a direction opposite to that of the planet's rotation. A retrograde orbit slowly decays, because the tidal bulge raised on the planet by the satellite is carried in the opposite direction by the planet's rotation; the bulge exerts a gravitational pull on the satellite from behind, slowing it down [*see top illustration on next page*]. Early calculations predicted Triton's demise in less than 100 million years, but a more recent study by Alan W. Harris of the Jet Propulsion Laboratory indicates that the orbital decay is exceedingly



TWO MOONS OF NEPTUNE are Triton and Nereid (*bars*). Triton, the large inner satellite, is about the size of the earth's moon. (In the photograph it appears far bigger than it really is.) Nereid is probably between 150 and 525 kilometers in diameter. Photograph was made by Christian Veillet with the Canada-France-Hawaii Telescope on Mauna Kea.



RETROGRADE ORBIT OF TRITON is decaying almost imperceptibly under the influence of tidal forces. As Triton moves in a circular orbit some 350,000 kilometers from Neptune, its gravitational field distorts the planet into a more ellipsoidal shape. (The two bodies are drawn to a common scale but the distance between them is disproportionately small; the size of the tidal bulges is greatly exaggerated.) Because the planet is not perfectly elastic and because it spins in a direction opposite to that of Triton's orbital motion, the near-side bulge is always slightly behind the satellite; its gravitation exerts a drag (*N*) on Triton, causing the moon to slowly lose altitude. The opposing force of the far-side bulge (*F*) is smaller.



REFLECTANCE SPECTRUM OF TRITON in the near-infrared (*bottom*) suggests that its surface consists primarily of methane ice and liquid nitrogen. Most of the absorption bands (reflectance troughs) match bands found in the spectrum of fine-grained methane frost. The band at 2.16 micrometers does not, but it is prominent in the nitrogen spectrum. The "best fit" model is a superposition of these two spectra and the spectrum of water frost.

slow, and that Triton will survive for 10 billion years or so.

Neptune and its moons lie half again as far from the sun as Uranus, and the region of the solar nebula in which they formed was probably colder. One would therefore expect Triton's chemistry to differ somewhat from that of the Uranian satellites. On the other hand, before data became available it was certainly expected that Triton's near-infrared spectrum would show the signature of very cold water ice. The absence of this signature was a striking feature of the first crude spectrum of Triton, obtained in 1978 by one of us (Cruikshank) and Peter M. Silvaggio, then at the Ames Research Center. Equally striking was the presence of a strong absorption band at a wavelength of 2.3 micrometers, which is characteristic of methane. The work showed that water may not be the dominant volatile material on the surface of objects at the edge of the solar system. The region of the solar nebula in which Neptune formed seems to have been profoundly different in temperature and composition from the region near Uranus.

The discovery of methane on Triton raised another exciting prospect: Triton must have an atmosphere. Methane is more volatile than water; in other words, the vapor pressure of methane ice at a given temperature—its tendency to sublimate into a gas—is greater than that of water ice. At the low temperatures prevalent near Uranus and Neptune virtually no water ice can sublimate, but methane ice sublimates readily. Although the absorption bands on Triton's spectrum could have been produced by either the frozen or the gaseous form of methane, both are probably present on the satellite; generally the presence of one implies that of the other.

We believe Triton may have an ocean as well. Collaborating with Clark in 1981, we obtained improved spectra that revealed another important feature: an absorption band at 2.16 micrometers that cannot be attributed to methane or to closely related hydrocarbons. We have tentatively attributed this band to molecular nitrogen. Ordinarily nitrogen does not absorb in the near-infrared, but the interaction of nitrogen molecules under high pressure does produce weak absorption bands. To produce the strong spectral feature we have observed, the nitrogen on Triton would have to be under very high pressure; given the satellite's low surface temperature, the nitrogen would have condensed to a liquid or a solid.

Our interpretation of the observations is that a large fraction of Triton is covered by liquid nitrogen at least a few tens of centimeters deep and possibly much deeper. The abundance of nitrogen appears to be much greater than that of methane. A small amount of methane may be dissolved in the nitrogen, but the data indicate methane exists as blocks of ice elsewhere on the surface.

We want to emphasize that the identification of nitrogen on Triton is tentative. If the nitrogen exists, it would not have to be in liquid form: Jonathan I. Lunine of the University of Arizona and Stevenson have proposed, on the basis of theoretical work, that it may be frozen solid. Further ground-based studies and *Voyager 2* data may help to settle the question.

Because of the high vapor pressure of nitrogen its presence in any form on Triton would imply that the satellite has a substantial nitrogen atmosphere; the atmospheric pressure at the surface would be between 10 and 30 percent of the level found on the earth. The earth and Saturn's moon Titan are the only other planet-size objects in the solar system known to have an atmosphere composed primarily of nitrogen. (If the earth were moved to the location of Triton, the low temperature would cause its atmosphere to condense to a liquid sea some 15 meters deep.) A nitrogen atmosphere on Triton would therefore be of considerable interest to planetary scientists. In particular it would bear on the question of the origin of nitrogen in the solar system: whether it originated as a pure substance in the solar nebula or whether it is derived from the photodissociation of ammonia gas into nitrogen and hydrogen. Ammonia is assumed to have been abundant in the nebula because hydrogen was abundant.

Solid ice, an ocean and an atmosphere on Triton might be expected to interact on seasonal and daily cycles, as they do on the earth. As a result of the inclination of its rotational axis Triton is subject to pronounced seasons. At present its south pole lies in permanent darkness and its north pole receives constant sunlight; in 82 years, when Neptune is on the other side of the sun, the situation will be reversed. Laurence M. Trafton of the University of Texas at Austin has speculated that the atmospheric abundance of methane in a particular region of Triton varies according to the season, increasing during the summer as methane ice sublimates and decreasing during the winter as methane gas freezes. Similarly, liquid nitrogen would freeze solid in the dark polar region. If the nitrogen sea is very shallow, it may even freeze at lower latitudes on a day-to-night cycle, in synchronism with Triton's rotation period of 5.877 earth days.

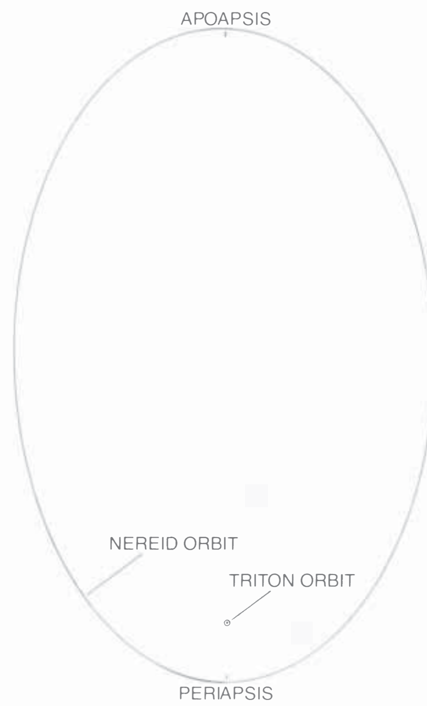
Another important attribute that Triton may share with the earth, as well as with Titan, is a complex organic chemistry. Both methane and nitrogen are colorless, yet Triton's color in the visible range is distinctly reddish. Clearly there must be an additional chemical component on Triton's surface. The red component may be produced by organic chemical processes like those proposed to account for the dark patches on the Uranian satellites. Sagan and Bishun N. Khare of Cornell have shown that ultraviolet irradiation of various mixtures of methane gas with ammonia, water vapor and other substances produces reddish hydrocarbon polymers. Similar compounds are formed, according to M. L. Delitsky of the Calgon Corporation, when methane dissolved in nitrogen is bombarded with charged particles. *Voyager 2* should determine whether Neptune is surrounded by Van Allen belts that could be the source of such particles.

The spacecraft will accomplish far more. Five hours after its closest approach to Neptune, on August 24, 1989, it will pass within 10,000 kilometers of Triton. It will transmit images of much of Triton's surface at a resolution of a few hundred meters—higher than that achieved during any previous flyby except the *Mariner 10* mission to Mercury and the Apollo missions to the moon. We may actually see methane ice blocks and the glint of sunlight reflected off the nitrogen sea; we may see the outlines of giant meteorite craters largely obliterated by the intense seasonal variations in Triton's weather. Moreover, *Voyager 2*'s infrared and ultraviolet spectrometers will determine the atmospheric abundances of methane, nitrogen and other gases, thereby testing crude models of the satellite's surface and atmosphere.

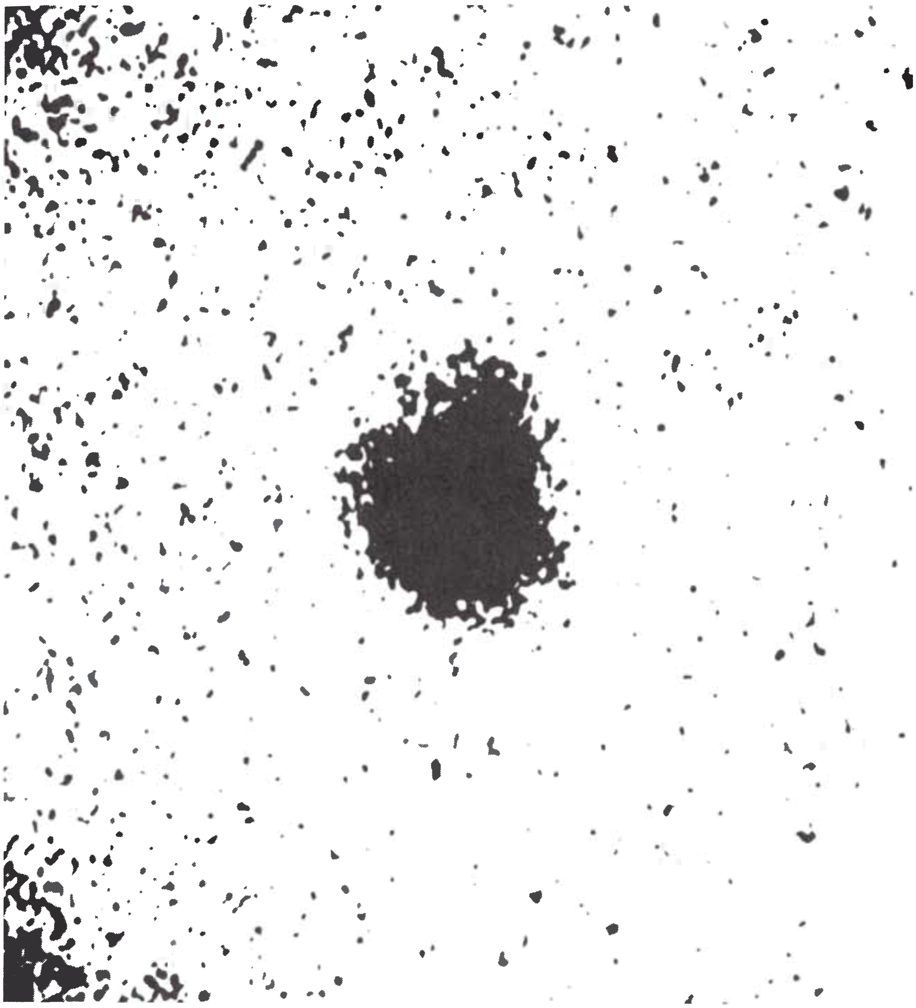
At the same time the spacecraft will add substance to studies of Triton's internal properties by providing the first reliable measurements of its mass and diameter. Recent radiometric measurements made by us and by others put the satellite's diameter at about 3,500 kilometers. This estimate could be wrong by as much as 40 percent, however, because it is based on the simplifying assumption that the solar energy absorbed by Triton is immediately reradiated as heat. A large, volatile ocean and an atmosphere would almost certainly store and redistribute a significant amount of heat, thereby violating the assumption.

Attempts to measure Triton's mass from the earth are hampered by the fact that Nereid, the only other satellite of Neptune, is too far away for its orbit to be measurably affected by Triton's gravitational field. Consequently workers have been forced to estimate Triton's mass from the almost imperceptible wobble it induces in the orbit of Neptune. Combined with the recent diameter measurements, such mass estimates yield a value of about eight grams per cubic centimeter for Triton's mean density, higher than that of any of the planets. This implausible result would imply that Triton is made mostly of iron or other metals, which is certainly not what one expects in the outer solar system. Precise mass and diameter figures derived from *Voyager 2* data will resolve the issue.

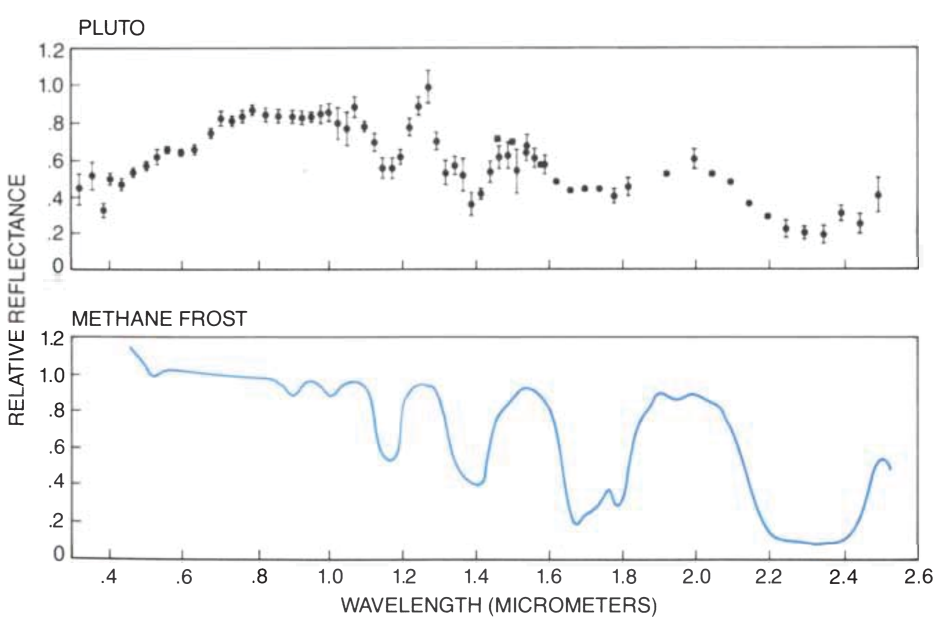
Finally, the spacecraft may settle the question of whether the Neptunian system has a third satellite or perhaps a ring. While monitoring the occultation of a distant star by Neptune in 1981, Harold J. Reitsema and his colleagues at the University of Arizona noted that the star dimmed several minutes before Neptune was to pass in front of it. The workers have suggested the star was occulted by a previously unknown satellite, one lying so close to Neptune that its image is lost in the planet's glare. In contrast William B. Hubbard, also of Arizona, has argued that Reitsema's occultation observations and those of others are best explained by positing a discontinuous ring around Neptune. If Hubbard is proved



ORBIT OF NEREID is a highly eccentric ellipse. At its closest approach (periapsis) the moon is 1.3 million kilometers from Neptune; at apoapsis it is 9.7 million kilometers away. Nereid's unusual orbit suggests it may have been captured by Neptune's gravity.



PLUTO'S MOON Charon is barely discernible as a bulge on the planet's image; here it is seen at the upper right. Charon is some 20,000 kilometers from Pluto, and it is probably between one-third and one-half the planet's size. The image was made by James W. Christy and Robert S. Harrington of the U.S. Naval Observatory, who discovered Charon in 1978.



PLUTO'S SPECTRUM in the near-infrared range shows at least four absorption bands characteristic of methane frost. The shape and strength of the bands, however, do not match those of the methane spectrum, indicating that Pluto has another surface component. A further discrepancy is found in the visible range (wavelengths between .3 and .7 micrometer), where Pluto has a reddish color because it reflects more red light than blue. The red component may be complex hydrocarbons derived from the photodissociation of methane.

correct, *Voyager 2*'s course may have to be changed: its present trajectory would take it right through the ring.

The spacecraft will not fly by Pluto, nor will any other probe in the foreseeable future. It is nonetheless appropriate to discuss Pluto here. Although it is a planet in a sun-centered orbit, accompanied by a satellite of its own, Pluto is comparable in size to Triton; at present it is also about the same distance as Triton from the sun, because its elliptical orbit has taken it temporarily inside the orbit of Neptune. The lessons learned from the Voyager encounters with Neptune and Uranus will expand our knowledge of Pluto as well as of Charon, its moon.

For nearly half a century after Pluto's discovery in 1930, the only thing known about it, other than its orbital parameters, was that it varied in brightness with a period of 6.4 days; the variation is attributable to the planet's rotation. Then in 1976 one of us (Cruikshank), collaborating with David Morrison and Carl B. Pilcher of the University of Hawaii, found spectrophotometric evidence that much of Pluto's surface is covered by methane ice. The high reflectivity implied by this finding suggested the planet was somewhat smaller and less massive than had been thought.

When Charon was discovered in 1978 by James W. Christy and Robert S. Harrington of the U.S. Naval Observatory, it became possible to calculate Pluto's mass. The results supported the hypothesis that Pluto is no larger than the earth's moon and is composed predominantly of volatiles. Charon is difficult to observe separately from Pluto—it is a mere appendage on the planet's image—and so its size and mass have not yet been calculated. It is probably between one-third and one-fifth the size of Pluto. Its mass must be a substantial fraction of the planet's, because its orbital period is the same as the planet's rotational period: the two bodies always keep the same face toward each other. Such synchronism can only arise when the satellite's mass is more than about 5 percent of the planet's mass. (In comparison, the mass of our own moon is less than 2 percent of the earth's; it keeps the same face toward the earth, but the earth's rotation is not constrained.)

Charon has a circular orbit oriented in a north-south direction, nearly perpendicular to the orbital plane of Pluto. This suggests that Pluto's equatorial plane is also roughly perpendicular to its orbital plane, a property once thought to be unique to Uranus. Earlier this year Edward F. Tedesco of the Jet Propulsion Laboratory, Richard P.

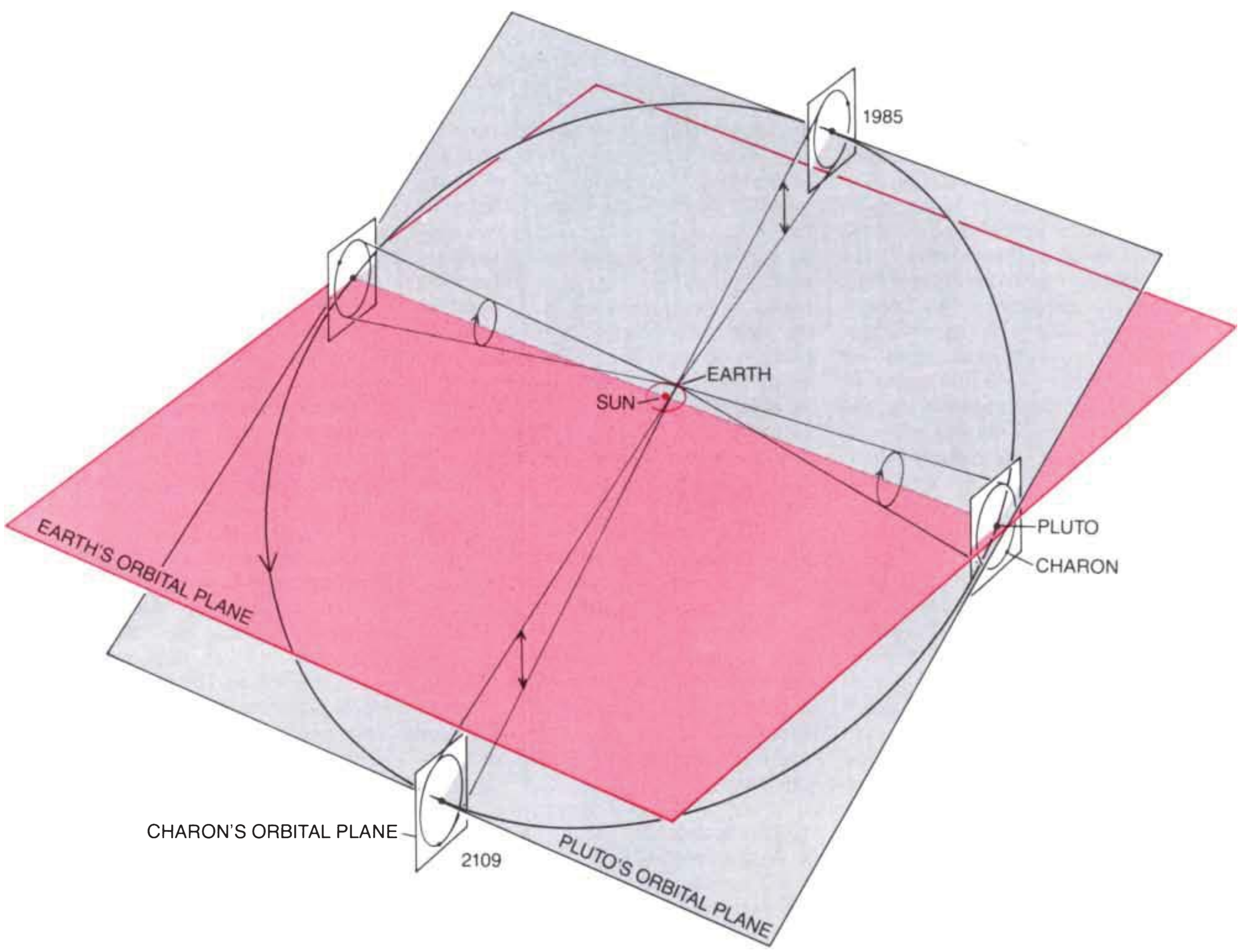
Binzel of the University of Texas at Austin and David J. Tholen of the University of Hawaii detected eclipses of Pluto (and occultations of Charon) for the first time. Eclipses can be observed only when the orbital plane of Charon is pointing toward the earth, which happens twice in Pluto's 248-year orbit. Observations of the current series of eclipses during the next few years should produce much better measurements of the dimensions of both bodies. It may be possible to determine whether they are similar in reflectivity and thus in surface composition.

The surface of Pluto is dominated by methane ice, but it must have another component as well. The strength of the methane absorption bands varies in different regions. Apparently the variation is associated with the variation in the planet's total brightness; bright regions seem to be those with the greatest coverage of methane ice. In dark regions a material of unknown composition covers the methane. On Pluto too the dark material may result from the photolysis of methane.

The presence of methane ice on Pluto implies, as it does on Triton, the existence of a tenuous methane atmosphere; Uwe Fink and Marc W. Buie of the University of Arizona have verified the presence of methane gas by means of spectral measurements of high resolution. Might Pluto also have a nitrogen sea? From the current data it is impossible to say, because even on high-resolution spectra the strong methane bands mask the region where a nitrogen band would appear. Nevertheless, in size and surface composition Pluto and Triton seem tantalizingly similar, and unlike the smaller, water-dominated Uranian moons.

The relation between Pluto and the Neptunian system is one of the enduring puzzles of the solar system. For a long time Pluto was considered an escaped satellite of Neptune, even though a mechanism that might have accounted for its transfer to a planetary orbit was never established. In fact, William B. McKinnon of Washington University has recently calculated that Pluto and Charon could not have survived an escape from Neptune without disintegrating. On the other hand, Triton's peculiar retrograde orbit suggests it may not be native to the Neptunian system. As McKinnon notes, the simplest hypothesis is that both Pluto and Triton condensed as planets in about the same region of the outer solar system—hence their chemical similarities—and that Triton was later captured by Neptune's relatively powerful gravitational field.

Of course, the simplest hypothesis may not be correct. The mysterious provenance of Pluto and Triton is another question that *Voyager 2,* together with the inventive use of telescopes on the earth, is likely to illuminate.



ECLIPSES OF PLUTO by Charon can be observed from the earth during two brief phases of Pluto's 248-year orbit; such observations were made for the first time earlier this year. Charon's orbit is nearly perpendicular to Pluto's orbital plane (*gray*) and to that of the earth (*color*). Near the points where Pluto is closest to and farthest from the sun, Charon's orbital plane is pointed toward the sun and the earth. Eclipses occur when the satellite passes in front of Pluto, occultations when it passes behind the planet. Both events produce a slight but measurable drop in the system's total brightness. The current series of events will continue for several years.