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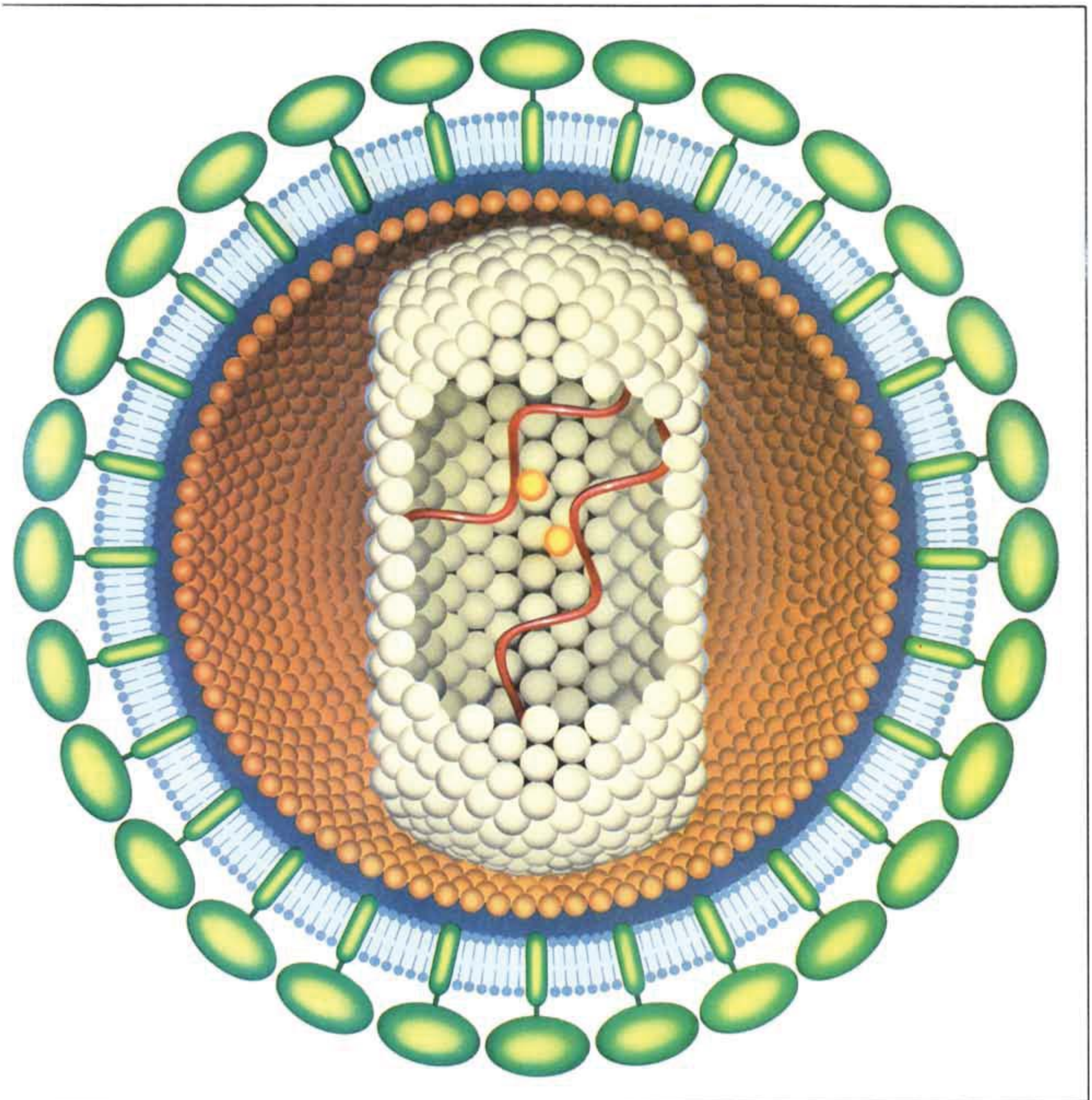

THE AIDS VIRUS

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Uranus

The giant blue-green planet visited last January by Voyager 2 *has one pole pointing toward the sun, and its magnetic field is askew. Its atmosphere is dense and icy, yet its winds resemble the earth's*

by Andrew P. Ingersoll

Uranus, in contrast to all other planets of the solar system, spins on its side, that is, its axis of rotation lies nearly in the plane of its orbit; the spin axes of the other planets are all nearly perpendicular to the orbital plane. How did the anomalous orientation of Uranus arise, and how does it affect the atmospheric circulation? Does the planet have a magnetic field, and if so, what is the field's orientation? These are a few of the questions *Voyager 2* set out to answer during the months around its closest approach to Uranus on January 24, 1986 [see "Engineering *Voyager 2*'s Encounter with Uranus," by Richard P. Laeser, William I. McLaughlin and Donna M. Wolff; SCIENTIFIC AMERICAN, November, 1986].

The encounter provided more new questions than answers, although fortunately it provided both in great numbers. That this is the way things ought to be is sometimes difficult to convey to an impatient public. During the joyful press briefing held by Voyager investigators on January 27, one reporter was bothered that scientists were still bewildered by the new findings and demanded to know why it was taking so long to explain them. Edward C. Stone of the California Institute of Technology, the project scientist for the Voyager mission, replied for all of us. "We are happily bewildered," he said. "We learn the most when we see things that we can't readily explain. If you see things you can explain right away, then you probably haven't learned very much. That means you probably already knew it."

In the months since the flyby, part but by no means all of the initial confusion over the Voyager data has given way to coherent interpretations. In what follows I shall recount some of what has been learned so far about Uranus. I shall focus on the planet itself; *Voyager 2*'s equally rich and fascinating findings concerning the Uranian moons and rings will be described in future issues of *Scientific American* by workers who are experts on these subjects.

Visually the most striking thing about Uranus, whether it is observed from the earth or from the vantage of *Voyager 2,* is just how unstriking it seems: it is a nearly featureless blue-green ball. When *Voyager 2* finally detected patterns in the Uranian clouds, the patterns turned out to be much smaller than the diameter of the planet and only approximately 5 percent brighter than their surroundings. From the earth Uranus' angular diameter is only about four seconds of arc. Since the earth's atmosphere blurs features smaller than about one arc-second regardless of the size of the telescope, ground-based observations can distinguish nothing at all on Uranus. One cannot even see that it is rotating.

Nevertheless, long before *Voyager 2* flew within 80,000 kilometers of Uranus investigators were aware of the strange orientation of the planet's rotational axis. The knowledge came from observing the orbits of the major moons and the rings. The orbits are all nearly circular, and they lie nearly in one plane. This observation suggested that early in its history the Uranian system had settled into a minimum-energy state, in which the moons and rings orbit in the planet's equatorial plane. Several forces conspire to push a planetary system toward this state, including gravitational interactions among its components, collisions with interplanetary debris and drag exerted by gas left over from the formation of the planet.

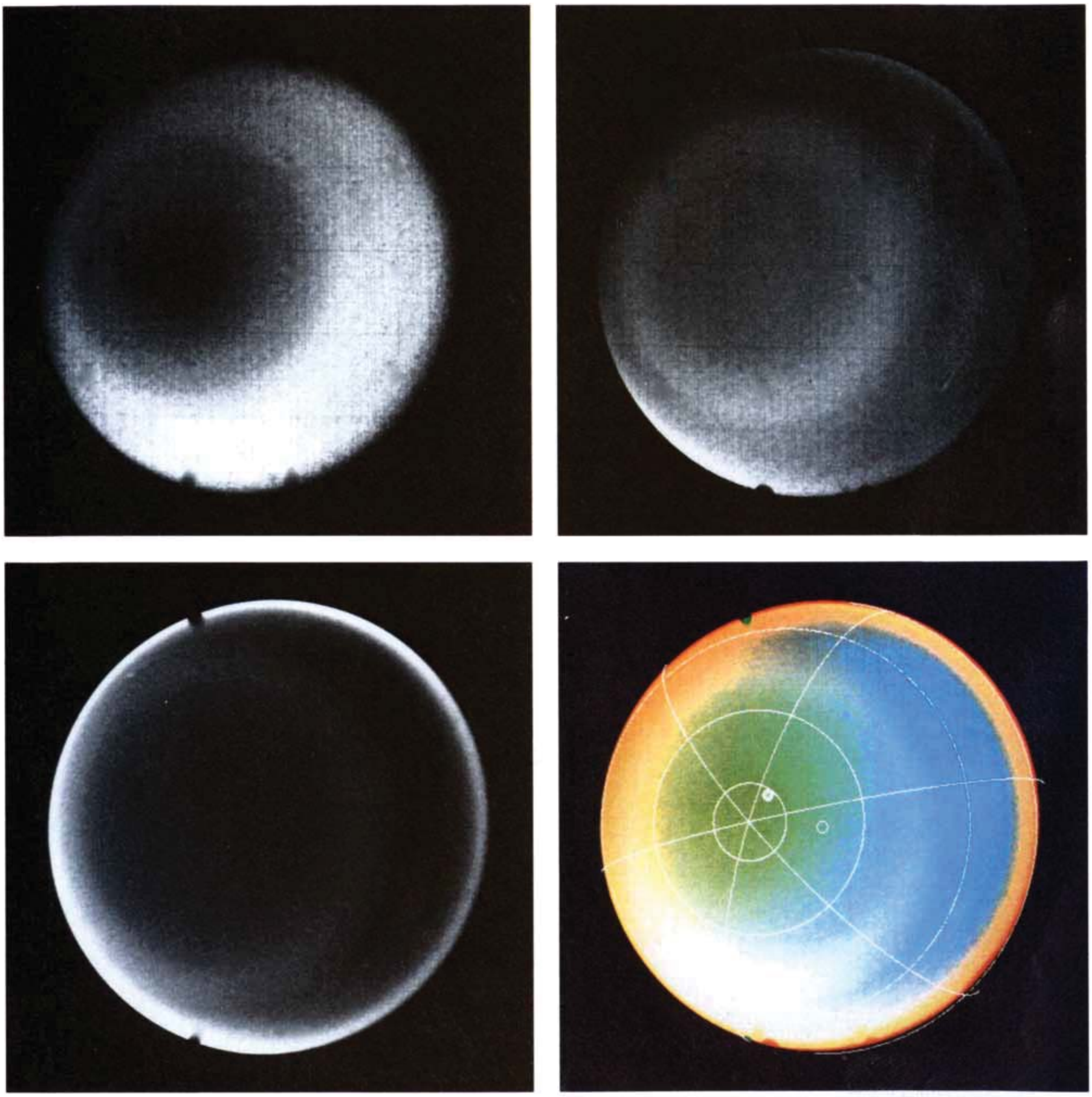
Precise observations have shown that the pole of counterclockwise rotation (which on Uranus, in contrast to the earth, is the south pole) is tilted 98 degrees with respect to the pole of the planet's counterclockwise orbit around the sun. At present the south pole points almost directly at the sun and the earth.

The mass, radius, temperature and atmospheric composition of Uranus were also known before the Voyager mission. The mass had been inferred from the orbital periods of the satellites; it is equal to about 14.5 earth masses. The radius, about 25,600 kilometers (four times that of the earth), had been determined by timing how long stars stay hidden behind the planet. The temperature at a pressure level of .4 earth atmosphere, some distance above the cloud tops, had been calculated by observing infrared (heat) emissions from Uranus; it turned out to be about 59 degrees Kelvin (−214 degrees Celsius). Finally, the atmospheric composition at the cloud tops had been deduced from the infrared spectrum, which includes the signatures of molecular hydrogen (H_2) and methane (CH_4). Selective absorption of reddish sunlight by the methane gives Uranus its blue-green color.

Although the top layer of the atmosphere is mostly gaseous hydrogen, the bulk of Uranus is made of heavier stuff. This conclusion is based on the planet's density, which is 1.27 grams per cubic centimeter. (Liquid water has a density of 1.) The density suggests that Uranus consists mostly of "ices," that is, of substances that would be frozen at the surface of the planet. Specifically, it must consist primarily of water, ammonia and methane, which, because they are compounds of the four most abundant reactive elements in nature (hydrogen, oxygen, carbon and nitrogen), are the most abundant ices in the solar system. At the low temperatures prevailing near the top of the Uranian atmosphere these compounds condense to form clouds of ice crystals. Methane freezes at the lowest temperature, and so it forms the top cloud layer. The methane clouds obscure the underlying ammonia and water clouds, which explains why the signatures of these substances are absent from the planet's infrared spectrum.

The picture that emerged from the ground-based observations put Uranus in a separate class with Neptune, somewhere between hydrogen- and helium-rich Jupiter and Saturn and the rocky, metal- and oxygen-rich planets of the inner solar system. It is worth noting that the classification is not what one would expect based on the most straightforward model of how the solar system formed. According to the model, the preponderance of the light elements hydrogen and helium should increase progressively with distance from the vaporizing heat of the sun. Yet Uranus, with its concentration of ices, contains more relatively heavy elements than Jupiter and Saturn do, and Neptune is heavier still. The icy components of Uranus and Neptune may have come from comets, which are stabler in the outer solar system, but the question remains open.

Uranus bridges a second gap between the Jovian and the terrestrial planets. It seems to have lost most but not all of the internal heat it had when it formed. As much as 30 percent of the heat radiated by the planet may come from its interior rather than

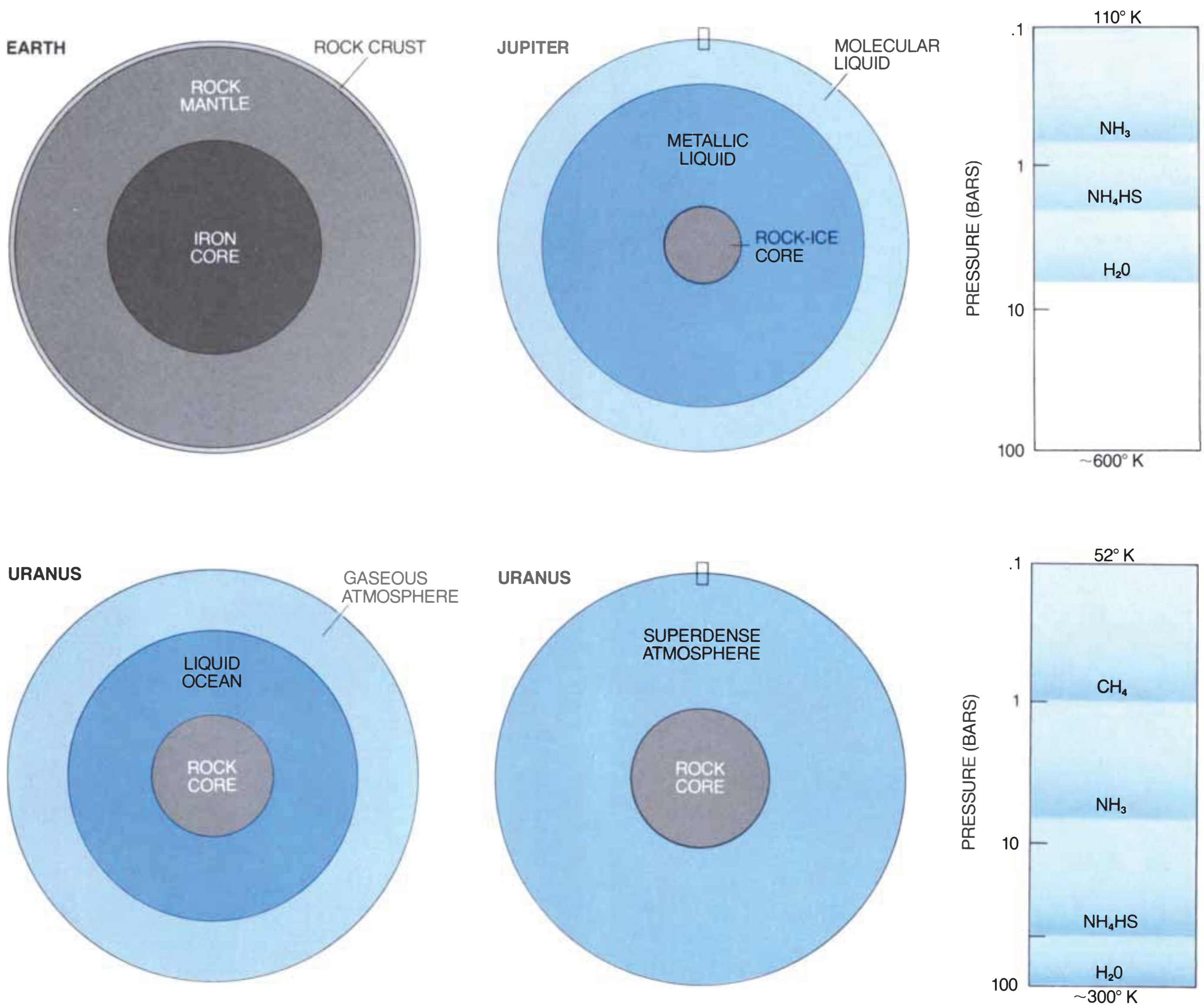


URANUS would be virtually featureless to an observer in space, but Voyager images in which the contrast has been drastically enhanced reveal cloud bands. The black-and-white images were made through three filters: violet (*top left*), orange (*top right*) and methane orange (the color selectively absorbed by methane gas) (*bottom left*); the false-color image is a composite of the three. The latitude-longitude grid on the false-color image shows that the cloud bands are centered on the pole and not on the point directly below the sun (*white dot*). The white circle indicates the point that was directly below the spacecraft when it made the images.

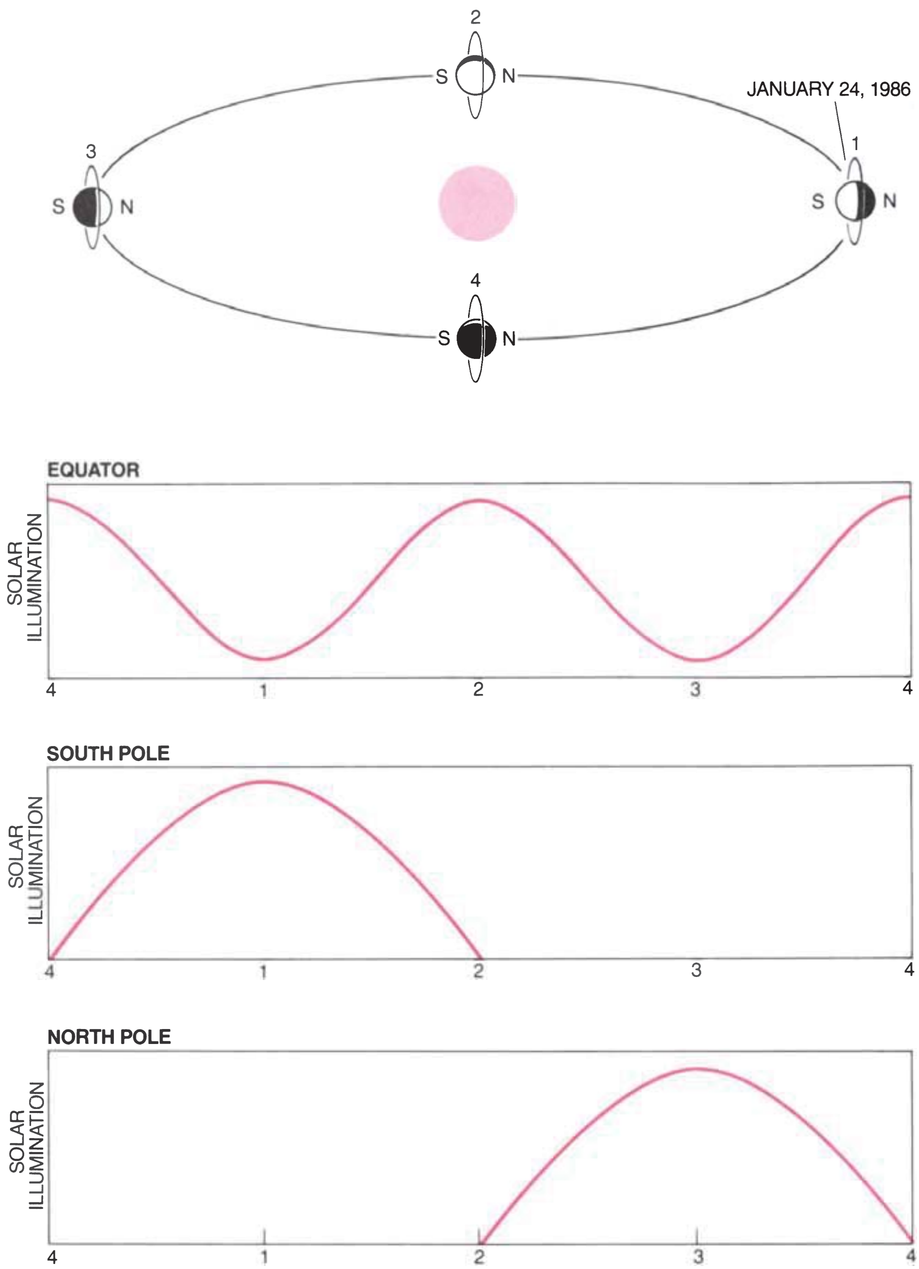
from the sun. The corresponding figure for the earth is .01 percent; for Jupiter and Saturn, which are much more massive and have therefore retained more of their internal heat, the figure is at least 70 percent. The strength of a planet's internal heat source is an important clue to its evolution. Atmospheric circulation patterns are also influenced by the extent to which the atmosphere is heated from below. One of the goals of the *Voyager 2* mission was to refine the rather uncertain estimate of Uranus' internal heat. The calculation requires the analysis of a large number of observations, however, and it has not yet been completed.

My own role in the Uranus flyby was in planning and analyzing the atmospheric observations, particularly those pertaining to clouds and winds. At first it was discouraging work, owing to the featurelessness of the planet. Commands to the spacecraft had to be programmed long before anything was visible on Uranus. Nevertheless, I and other workers interested in the Uranian atmosphere proposed that the spacecraft make many images of the planet. Our colleagues on the imaging team (which was then waggishly called the "imagining team") agreed—partly because they were sympathetic and partly because, until the day before the encounter, the planet was the only thing large enough to fill the field of view of *Voyager 2's* narrow-angle camera.

During the last few months of 1985 the planet grew steadily in the field of view, but it remained as dull as ever. The problem was that variations in sunlight dominate the variation in brightness across the planet's disk; real atmospheric features are washed out by the solar glare. Fortunately the sun-



INTERNAL STRUCTURES of the earth, Jupiter and Uranus are compared. (Their relative sizes have been distorted; Uranus is about four times and Jupiter more than 11 times the size of the earth.) The earth, like Mercury, Venus and Mars, is a dense, rocky planet consisting mostly of metals and their oxides. Jupiter, like Saturn, consists mostly of hydrogen and helium, which form a molecular liquid in the outermost layer and a metallic liquid—that is, a mixture of protons and free electrons—under the intense pressures prevailing at greater depths. Uranus, like Neptune, is intermediate between the terrestrial and the Jovian planets, consisting mostly of water, ammonia (NH_3) and methane (CH_4) "ices." In the three-layer model of Uranus (*left*) melted ices form a liquid "ocean" between the rocky core and the gaseous hydrogen-helium atmosphere. Voyager data, however, favor a two-layer model (*right*) in which the gases and ices are mixed in a dense atmosphere. Near the visible surface layers of the atmosphere of Jupiter and Uranus, ammonia, ammonium hydrosulfide (NH_4HS) and water are thought to condense (in a sequence determined by their condensation temperatures) to form icy clouds. Uranus is cold enough to allow methane to condense above the other clouds.



SEASONAL CHANGES in solar illumination on Uranus are vastly different from the changes on other planets because the planet lies on its side. The Uranian year is about 84 earth years long. At present the south pole is pointed toward the sun and the north pole is in constant darkness; 42 earth years from now the conditions will be reversed. The equator, now in constant twilight, has two such winters and two summers every year.

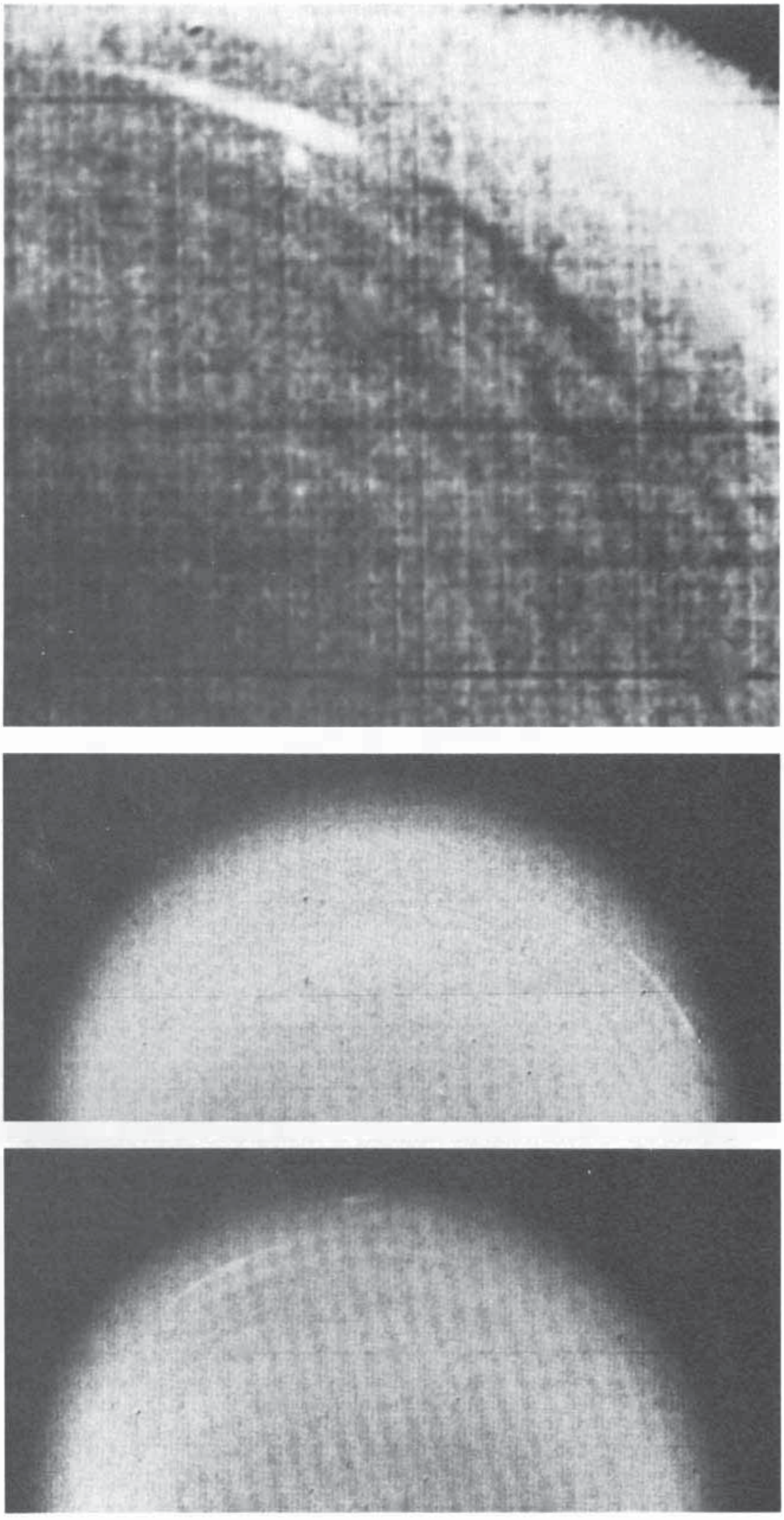
light distribution is regular—the planet is brightest at the subsolar point near the south pole and grows progressively darker toward the equator—and so it can be modeled mathematically. Not long after Thanksgiving, Charles Avis, Robert H. Brown and Torrence Johnson of the Jet Propulsion Laboratory worked out a mathematical expression for the brightness variation on a hypothetical planet similar to Uranus but truly featureless. When the model was subtracted from the observed brightness variation on Uranus, faint cloud features became visible.

As I noted above, the features are only a few percent brighter than their surroundings, but the contrast could be exaggerated and displayed in false color. The enhanced images revealed a series of cloud bands concentric with the pole of rotation. Superposed on the bands and between them were smaller features that circled the pole counterclockwise, each at a constant latitude. Features at different latitudes circled at different rates, with periods ranging from 14 to 17 hours. Clearly, therefore, the clouds were not simply being carried by the planet's rotation. We had observed winds.

At last, after months of expectation, we had a scientific result, and a significant one at that. First, the cloud bands did not have to be concentric with the pole, but they were. Second, the winds did not have to blow in an east-west direction, but they did. Both the banding and the east-west winds are similar to what one finds on Venus, the earth, Jupiter and Saturn. Before *Voyager 2*'s encounter with Uranus one might have expected its atmospheric circulation to be different. On Uranus as on the other planets the sun supplies most of the energy that drives the circulation. At the time of the encounter the sun was almost directly above the south pole, the north pole had been in darkness for about 20 years and the equator was in constant twilight. The sunlight distribution was thus completely different from that on the other planets, whose axes are much less tilted. And yet the atmospheric circulation was similar.

Apparently the sun, although it supplies the energy that drives a planet's atmospheric circulation, does not determine the pattern of the circulation. Instead the pattern is dominated by the effects of a planet's rotation. The rotation gives rise to what is called the Coriolis force, which steers the winds into zones of constant latitude. If an atmospheric parcel curves away from its latitude zone, the Coriolis force sends it spinning back. Spacecraft observations of the planets, particularly Uranus, have shown just how important the Coriolis force is. We have learned that atmospheric circulations are not so much forced by the sun as they are coasting under their own inertia.

By early January of 1986, when observations of cloud features on Uranus were already in hand, the investigators involved in *Voyager 2*'s magnetic field and charged-particle experiments were still anxiously awaiting their first results. If Uranus had no magnetic field, these investigators would have nothing to observe but the solar wind of charged particles streaming past the planet; the planet's only effect would be to create a wake in the flow. There would be nothing to say about dynamo processes and electrically conducting regions inside the planet, other than that apparently there were none. Furthermore—and this was of concern to atmospheric scientists as well—there would be no way to determine the planet's internal rate of rotation. On the giant planets such as Uranus, which lack a solid surface, an internally generated magnetic field provides the only fixed reference frame against which atmospheric motions can be measured.



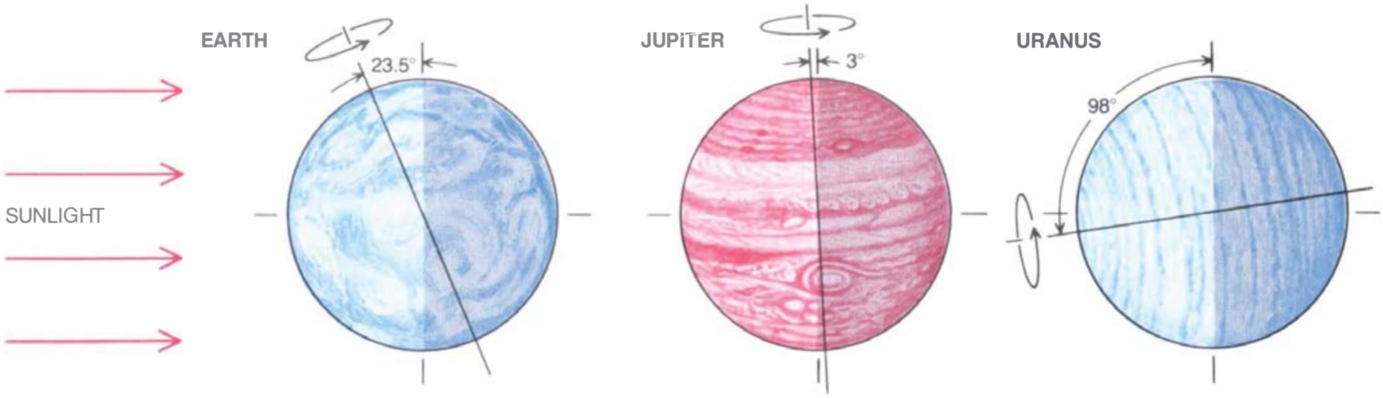
BRIGHT CLOUD FEATURES on Uranus were observed by *Voyager 2* within and between the concentric cloud bands. The clouds move counterclockwise around the pole of rotation; features at different latitudes move at different speeds, indicating they are being carried by east-west winds whose intensity varies with latitude. The feature in the closeup view (*top*) is probably the plume of a convective updraft. By tracking it in a time-lapse sequence one can measure the wind speed. In the middle photograph the feature is at the two o'clock position; in the bottom photograph it has moved to the 11 o'clock position.

Dejection grew among the members of the *Voyager 2* team as the spacecraft passed the point at which theoretical models had predicted that the effects of a magnetic field would begin to be observed. Then, only five days before the closest approach, the spacecraft detected radio signals and charged-particle streams emanating from Uranus. By analogy with other planets the radio emissions had to come, either directly or indirectly, from charged particles spiraling around magnetic field lines. The modulation of the emissions suggested that the Uranian magnetic field was tilted in relation to the planet's axis and was therefore wobbling as the planet rotated.

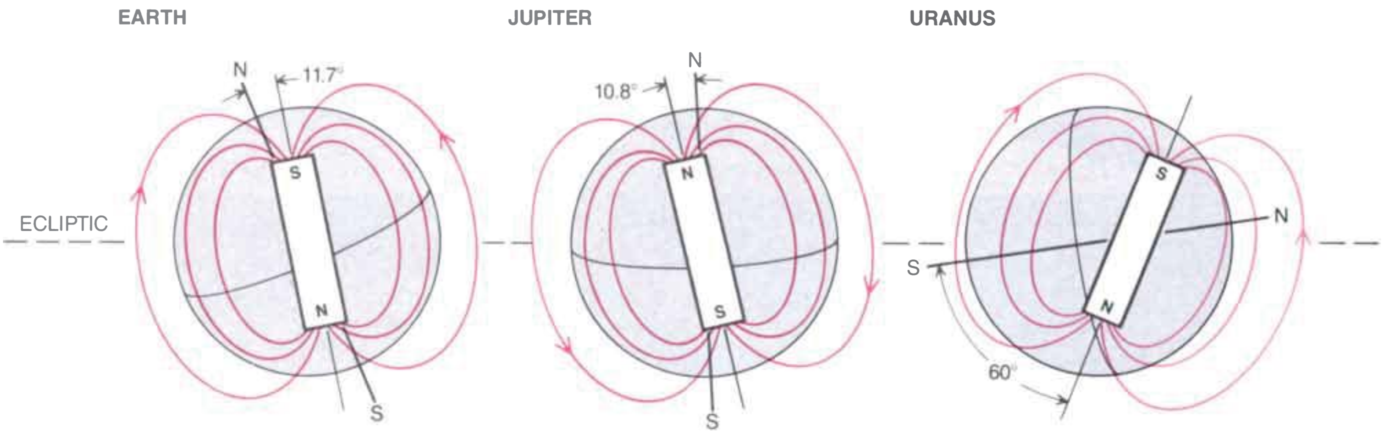
At this point *Voyager 2* had still not entered the magnetic field. On the sunward side of the planet the field is confined to a comparatively small region by the solar wind, which deforms the field and sweeps it into a long tail behind the planet. Right outside this region (the magnetosphere), where the field can just hold its own against the solar wind, a bow shock forms. (The bow shock is analogous to the shock wave that precedes an airplane traveling at supersonic speeds, but it is an electromagnetic disturbance rather than a pressure wave.) *Voyager 2* crossed the bow shock on January 24, only 10 hours before its closest approach to the planet. The magnetometer team, under the leadership of Norman F. Ness of the Goddard Space Flight Center, was soon mapping the shape and strength of the Uranian magnetic field.

It was not as simple a field as had been expected. Every other planetary magnetic field is dominated by a dipole component, the equivalent of a small but powerful bar magnet at the center of the planet. On the earth, Jupiter and Saturn the hypothetical bar magnet is nearly parallel to the planet's rotation axis. (The tilt angle of the earth's field, 11.7 degrees, is the largest.) Quadrupole and octupole components describing irregularities in the dipole field are important mainly inside these three planets, near the electrically conducting core whose fluid motions are thought to generate the field. On Uranus, in contrast, the bar magnet is tilted by 60 degrees with respect to the rotation axis, and the other field components are almost as strong as the dipole. To suppress these components and make a pure dipole model fit the data one has to move the dipole off center by 30 percent of the planet's radius.

Might the uncommonly large tilt of Uranus' magnetic axis be associated with the unusually large angle between the rotation axis and the orbit axis?



EAST-WEST WINDS dominate the atmospheric circulation on Uranus, much as they do on the earth and Jupiter, even though the distribution of sunlight is entirely different on Uranus as a result of the unusually large tilt of its spin axis. The similarity suggests that the Coriolis force arising from a planet's rotation has a dominant influence on its atmospheric circulation pattern.



MAGNETIC FIELD of Uranus is tilted by 60 degrees with respect to the planet's spin axis, and the hypothetical dipole magnet that models the field most accurately is offset from the center of the planet. (The south end of the dipole is the one toward which a compass needle would point.) In contrast, the dipole fields of the earth and Jupiter are tilted only slightly, and they are not offset.

For that to be the case the interior of Uranus, where the magnetic dynamo resides, would have to "know" where the sun is, because the sun defines the orbit. One possibility is that the interior is affected by the sun's differential gravitational pull: the pull is stronger on the day side than on the night side of the planet. My colleague David J. Stevenson of the California Institute of Technology has shown, however, that this tidal effect is much too slight (Uranus is 19 times as far from the sun as the earth is) to have a significant impact on the dynamo region inside the planet.

Ness and his co-workers have speculated that Uranus may be undergoing a magnetic field reversal, which might explain both the tilt of the magnetic axis and the offset of the dipole. (On the earth there is geologic evidence of numerous field reversals, although the fraction of time spent going from one polarity to the other is small.) Alternatively, the offset may simply indicate that the dynamo region is closer to the surface on Uranus than it is on other planets. Uranus contains a lot of water and ammonia, which become good electrical conductors at lower pressures (and hence at shallower depths) than the hydrogen and helium that predominate on Jupiter and Saturn.

In truth, however, neither the tilt of Uranus' magnetic axis nor the offset of the dipole has been adequately explained. Yet one should remember that no planetary dynamo, including the earth's, is well understood, primarily because observational data on the interior of a planet are so hard to come by. The Uranian magnetic field appears strange; on the other hand, if a larger sample of planets were available, one might find that a substantial number have fields inclined by 60 degrees or more.

The magnetosphere of Uranus extends to an altitude of at least 590,000 kilometers on the day side of the planet and to about six million kilometers on the night side. Like the magnetospheres of other planets, it is filled with an ionized gas, or plasma, composed of equal numbers of positive ions (primarily protons) and electrons. The particles are trapped in the magnetic field, and they oscillate between the north and south magnetic poles. Their average energy increases toward the planet. Indeed, the *Voyager 2* charged-particle team headed by Stamatios M. Krimigis of Johns Hopkins University found that Uranus has radiation belts (regions of high-energy particles) similar to the earth's Van Allen belts.

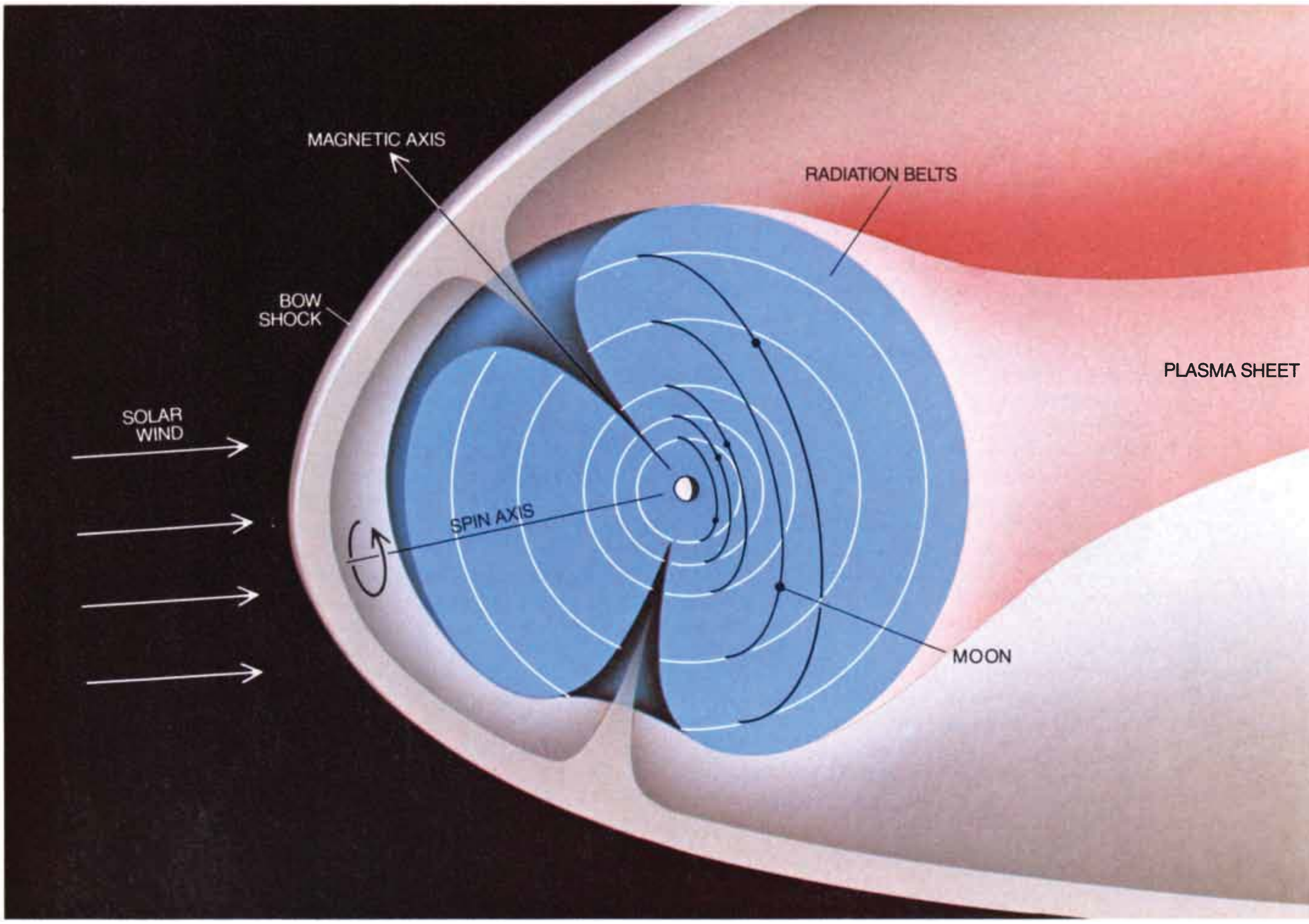
The radiation in the Uranian belts is so intense that within a few million years it can cause significant damage to exposed surfaces. This effect may explain the dark color of the rings and the dark patches on the moons. The moons and the rings orbit within the radiation belts, and as a result they sweep up high-energy particles. If, as is generally thought, their surfaces consist in part of methane ice, then radiation-belt protons may break down the methane and convert it into complex hydrocarbons that have a dull, dark color.

Voyager 2 spent more than two Uranian days in the magnetosphere. Since the magnetic field is fixed to the planet, the planet's rotation rate could be determined from the periodic fluctuations of the field intensity. It could also be calculated from the radio emissions that had been the first sign of a magnetic field on Uranus. The emissions come from near the magnetic poles, and so they too fluctuate periodically as the magnetic axis precesses about the rotation axis. The planetary radio-astronomy team headed by James W. Warwick of Radiophysics, Inc., in Boulder, Colo., observed more than 10 cycles of the radio emissions. According to the workers' calculations, which agree with those based on the magnetic field intensity, Uranus rotates once every 17.24 hours. The best guess before the flyby had predicted a somewhat faster rotation.

The internal rotation rate of a giant planet, in conjunction with the size of its equatorial bulge, is a sensitive probe of its internal structure. The faster the rotation is, the stronger is the centrifugal force on the planet, the more mass is shifted toward the equator and the larger is the equatorial bulge. The size of the bulge also depends on the distribution of mass inside the planet: if two planets have the same mass, radius and rate of rotation, the one that has more of its mass concentrated near the center will have a smaller bulge. The bulge can be measured visually, or its size can be inferred from its gravitational effect on the orbits of the planet's moons and rings. In the case of Uranus the equatorial diameter of the planet is about 2.4 percent larger than the polar diameter.

Even before the Voyager encounter William B. Hubbard and Joseph J. MacFarlane of the University of Arizona had used this figure and the best estimate of the rotation rate to evaluate different models of Uranus' internal structure. The models differ in the relative proportions and degree of mixing of three principal components: rock (metals and metallic oxides), ice (water, methane and ammonia) and gas (hydrogen, helium and neon). One popular model had the three components entirely separate; a gaseous atmosphere overlay a deep "ocean" of ices melted by the high temperatures inside the planet, and the ocean surrounded a rocky core. Hubbard and MacFarlane found that this mass distribution was too centrally concentrated to produce Uranus' rather large equatorial bulge.

When *Voyager 2*'s lower value for the rotation rate is introduced into the calculation, the bulge produced by the three-layer model becomes even smaller and the discrepancy with the observations becomes even greater. Instead the spacecraft data favor a two-layer model, in which the ices and gases are mixed in a dense atmosphere



MAGNETOSPHERE of Uranus is produced by the interaction of its magnetic field with the solar wind. A bow shock analogous to the shock wave preceding a supersonic aircraft forms "upstream" from the magnetic field. The magnetosphere, which begins slightly inside the shock front, is filled with a plasma of protons and electrons, some of which probably come from the solar wind and some of which come from hydrogen in the planet's atmosphere. The charged particles are trapped in the magnetic field; those with high energy oscillate back and forth between the magnetic poles, forming torus-shaped radiation belts. Low-energy particles are

extending from the core to the visible layers of the planet. The bulk of the atmosphere is probably water. Toward the top of the atmosphere, where the temperature declines rapidly to a minimum of 52 degrees K., the water, ammonia and methane condense (in that order) to form thick, icy cloud layers. The top layer, the methane, is visible in the Voyager images. Above it lies a thin upper atmosphere, a gaseous mixture that consists primarily of hydrogen with a little helium and neon.

The internal rotation rate deduced from the Uranian magnetic field came as a surprise to meteorologists, because the 17.24-hour rotation period is longer than the periods of the cloud features seen in the Voyager images. In other words, the atmosphere at the level of the cloud tops is rotating faster than the interior of Uranus, at least in the 25-to-70-degree latitude band where features were observed. The difference is greatest at high latitudes, where the features circle the poles in 14 hours, and it gets progressively smaller toward the equator. Near the equator the relation seems to be reversed, so that the atmosphere rotates slower than the interior.

most abundant in the plasma sheet, which separates the north magnetic hemisphere from the south. As the moons orbit the planet in the plane of the equator, they sweep out particle-free lanes (*white lines*).

The distribution of wind intensities is surprising for the same reason that the dominance of east-west winds on Uranus is surprising: because it closely resembles the pattern on the earth. For example, in the earth's mid-latitudes the circulation is dominated by high-altitude eastward jet streams. The pattern is a direct consequence of the fact that the Equator is hotter than the poles: the latitudinal temperature gradient creates a pressure gradient aloft that is balanced by the Coriolis force, resulting in eastward winds. Since Uranus lies on its side, one would expect its poles to be hotter than its equator rather than colder. Nevertheless, the rapid rotation of cloud features at high latitudes indicates that Uranus has winds like the earth's jet streams.

There are two ways to explain the apparent contradiction. First, the Uranian circulation may be driven not by temperature gradients but by density gradients associated with condensation and precipitation. When water vapor condenses in part of the earth's atmosphere, the density of the atmosphere in that area changes by less than 2 percent. The dense Uranian atmosphere, however, might be as much as 50 percent water. If for some reason a substantial part of the water near the Uranian equator were to condense, the resulting density gradient might mimic the earth's temperature gradient and drive a poleward flow. (A terrestrial analogue would be ocean currents that are driven by salinity differences rather than by temperature gradients.)

Alternatively, the poles of Uranus may not really be hotter than the equator even though they receive more sunlight. The *Voyager 2* infrared spectrometer team, led by Rudolph A. Hanel of the National Aeronautics and Space Administration's Goddard Space Flight Center, measured the temperature from one pole to the other just above the cloud tops, at a constant pressure level of about .6 earth atmosphere. (The pressure at the cloud tops is roughly one earth atmosphere.) The group found the same temperature, 64 degrees K., at both poles and at the equator; in the mid-latitudes of both hemispheres the temperature was between one and two degrees lower.

Theoretical models had actually predicted that the two poles would have nearly the same temperature. Sunlight is so weak at Uranus that seasonal temperature swings should be no more than about two degrees K. Moreover, James Friedson of Caltech and I have calculated that winds may limit the seasonal swings by transferring heat from one hemisphere to the other; the cooling of the dark pole may also be balanced by enhanced convection of internal heat. Still, none of the models can explain why the equator should be as warm as the poles. Apparently heat circulates in the Uranian atmosphere in a more complex way than the models envision.

The atmosphere of Uranus does not stop at the planet's visible surface. Above the clouds there is a tenuous upper atmosphere consisting primarily of hydrogen molecules. (The breakdown of this hydrogen by sunlight and by charged particles may be the major source of the protons and electrons that make up the radiation belts.) The temperature in the upper atmosphere rises to a warm 750 degrees K., causing it to balloon 6,000 kilometers above the cloud tops. Sunlight alone cannot account for the high temperature; another source of energy must be involved.

Whatever the energy source is, it probably also underlies the curious emissions observed by the ultraviolet-spectrometer team under the leadership of Lyle Broadfoot of the University of Arizona. The emissions were detected only on the day side of Uranus, indicating that sunlight is required as a stimulus. A similar phenomenon was observed at Jupiter and Saturn. It has been named electroglow on the theory that electrons may be exciting hydrogen molecules in the upper atmosphere of all three planets. How the electrons get their energy is not known.

A similar degree of uncertainty persists concerning the answer to the biggest question about Uranus: Why is it spinning on its side? Although *Voyager 2* did not find a smoking gun at Uranus, the spacecraft has over the years found dramatic evidence of violent collisions in the early solar system. The moons of Jupiter, Saturn and Uranus all bear the scars of impacts large enough to have nearly disrupted them. As the debris orbiting the newly formed sun aggregated into planet-size bodies, the final collisions would have been the largest; at least one body the size of the earth probably collided with what is now Uranus. A large, off-center impact could have knocked the planet onto its side. This is the hypothesis most investigators now accept. It remains to be confirmed or disproved by future spacecraft missions.