DOUBLE SUPPLEMENT: SATURN AND THE SOLAR SYSTEM

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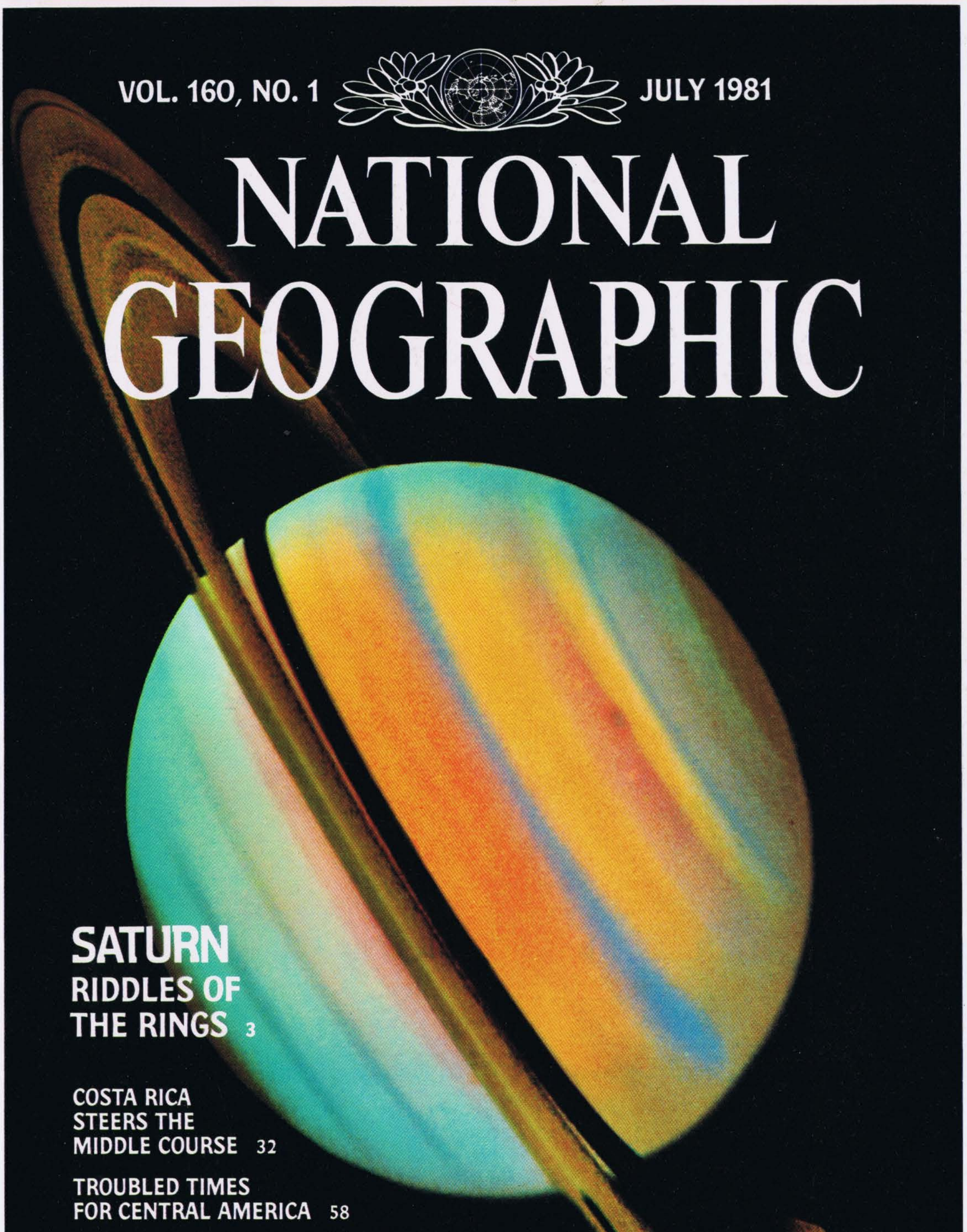

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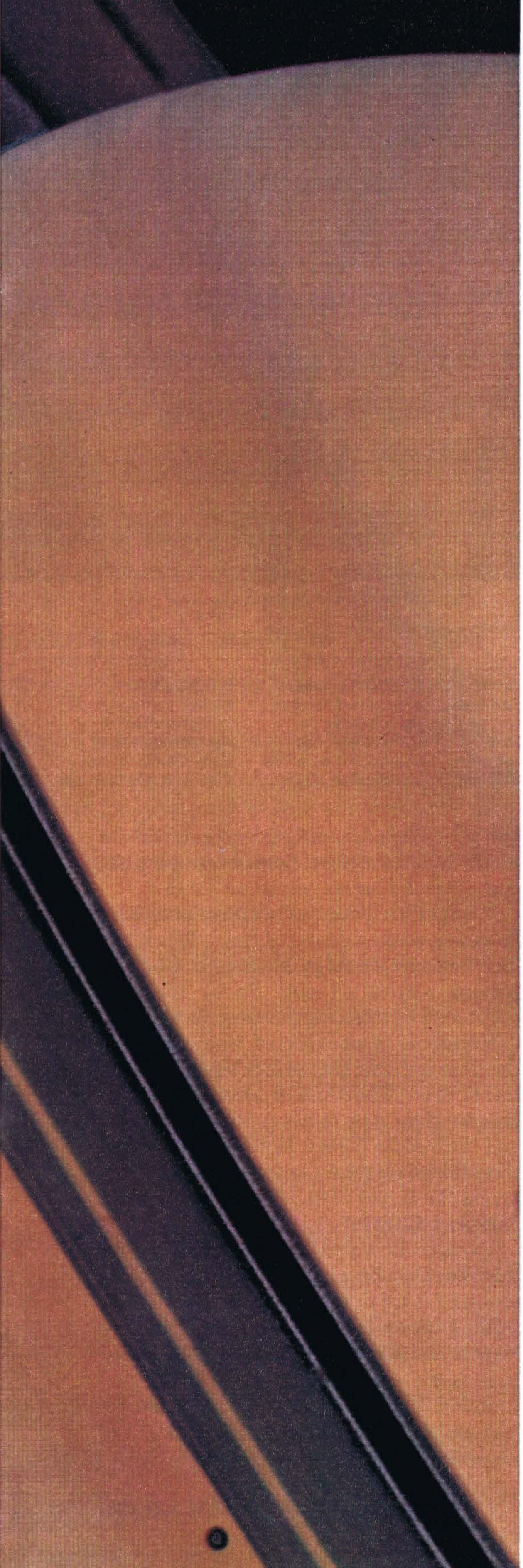


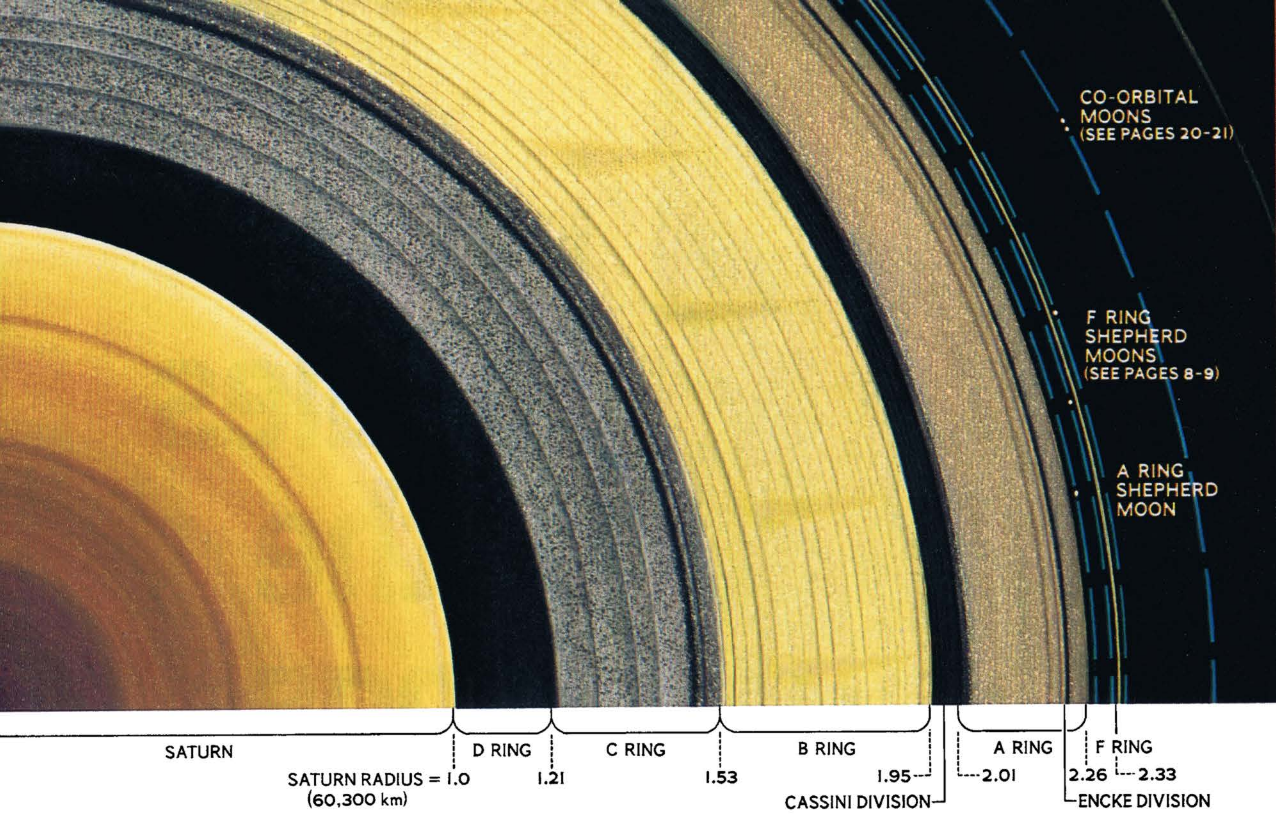
VOYAGER 1 AT SATURN

Riddles of the Rings

Still 13 million kilometers away, Voyager 1 takes a portrait of Saturn and two of its moons, one casting its shadow on the cloud tops below the rings. Shortly, Voyager would find the bizarre reality—puzzles in the rings and enigmas on the moons. With worlds yet to reveal, the unmanned Voyager spacecraft have proved themselves instruments of wonder on the frontier that forever recedes.

By RICK GORE
NATIONAL GEOGRAPHIC SENIOR WRITER

Photographs by NASA



Saturn's rings

SATURN, largely hydrogen and helium with a rocky Earth-size core, is the second largest but least dense planet.

D RING, confirmed by Voyager 1, extends from 12,700 kilometers above Saturn perhaps to the planet's atmosphere.

C RING, composed of dozens of ringlets yet relatively transparent, has at least one eccentric (noncircular) ringlet.

B RING shows spokes, perhaps small particles affected by electromagnetic or electrostatic forces, that form and fade away.

NOVEMBER 10, 1980. The Voyager 1 spacecraft is a billion miles and more than three years from home. Deep in the outer solar system, it is rapidly approaching Saturn. In this super-cold, alien domain, where perpetual ring glow has banished night, Voyager is photographing a pale yellow giant, a turbulent ball of primordial gas that more resembles a star than the inner planets we know.

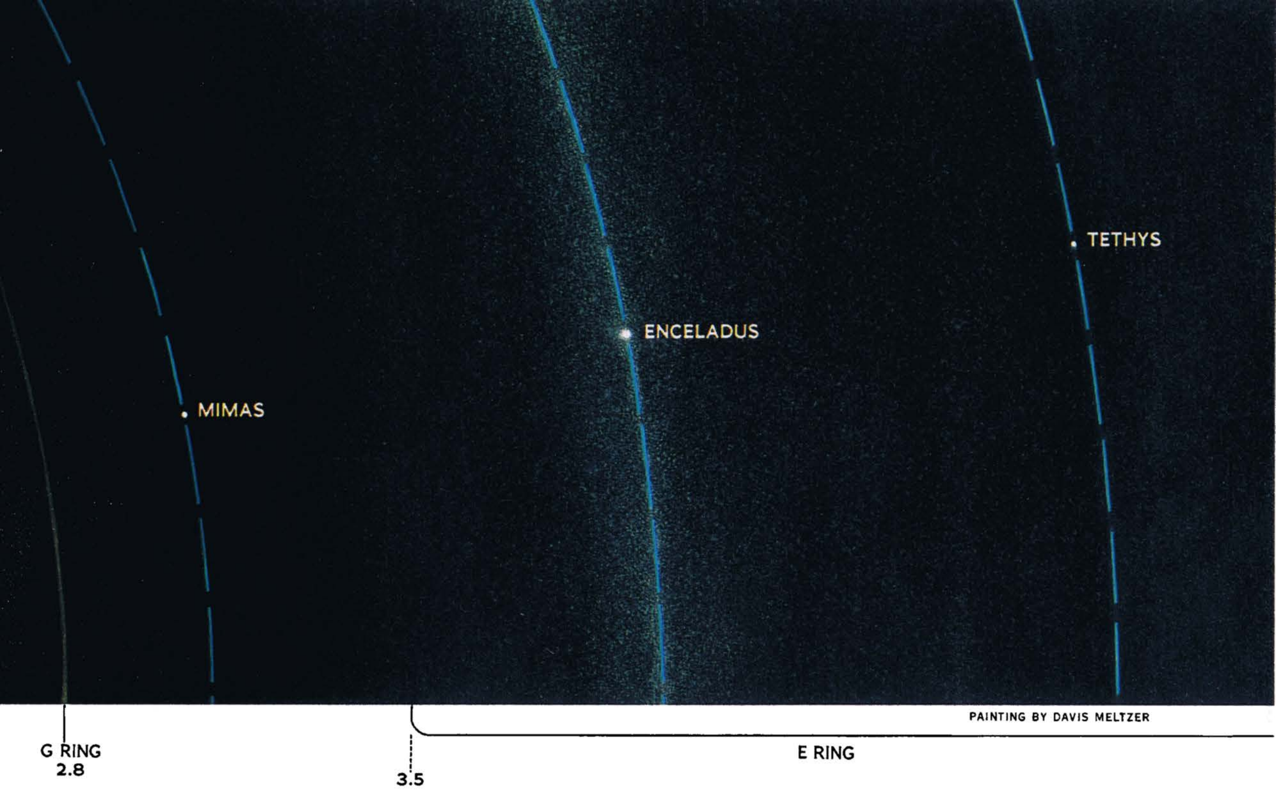
In two days Voyager will fly within 50,000 kilometers (30,000 miles) of those three bright rings that astronomers refer to simply as A, B, and C. It will explore the faint, recently discovered outer rings, E and F, and try to confirm sightings of a tenuous D ring close to the surface of the planet.

Voyager is also ready to unveil Saturn's moons, which range from the size of a small asteroid to mammoth Titan, larger than the planet Mercury. Most of the 15 known are mid-size—200 to 1,500 kilometers across—and made not from sand and stone and ores but from the icy stuff of comets. Big, mysterious Titan is known to have an atmosphere, and scientists are hoping that clouds will not totally hide its surface. Some even speculate that life could have evolved on Titan.

Voyager has been paying most attention, however, to the celebrated rings. When Galileo first saw the rings, he thought God was playing a trick on him. Today scientists could well be thinking the same thing.

Hundreds of unexpected ringlets within the rings are emerging before Voyager's electronic eyes. The Cassini Division, a supposedly clear zone between the outer A ring and the middle B ring, is alive with at least three dozen ringlets. Curious spokes radiate across the B ring. The close-in C ring looks dark and different.

Voyager is watching two small moons that seem to be playing tag as they race around Saturn in almost the same orbit. The trailing moon is traveling faster than the leader, and should catch up with the leader in January 1982 (pages 20-21). The two presumably have been playing this game for billions of years. Through what sleight of physics do they avoid colliding?



PAINTING BY DAVIS MELTZER

CASSINI DIVISION is seen from Earth as an empty space; it contains several evenly spaced bands of ringlets.

A RING has at its outer boundary a newly discovered moon.

F RING, bounded by shepherd moons, has an eccentric shape and irregular pattern; two of its strands appear intertwined.

G RING, narrow and diffuse, probably is accounted for by gravitational forces of undiscovered shepherd moons.

E RING is a broad, diffuse band of small particles that may be fed by material escaping from Enceladus.

Voyager has also spotted three "shepherd moons." Two of these moons orbit along the inner and outer edges of the F ring (pages 8-9), which wreathes the three bright main rings like a ribbon. Using odd gravitational tricks, these moons herd back in bounds particles trying to escape the F ring.

These F ring moons, along with a third little moon just 800 kilometers outside the bright A ring, seem to be shepherding the entire main ring system. These unimpressive chunks of ice apparently hold in place countless trillions of ring particles, spanning 63,000 kilometers.

AN AURA OF ASTONISHMENT pervades the Jet Propulsion Laboratory in Pasadena, California. Twenty months earlier this same Voyager had discovered so many marvels at Jupiter—a complex, storm-tossed atmosphere, a thin ring, volcanism on one moon, and evidence of ancient Earth-like crustal movements on another—that its Saturn encounter had threatened to be anticlimactic.*

"We were afraid Voyager's Saturn encounter was going to be a bust," one project scientist confides.

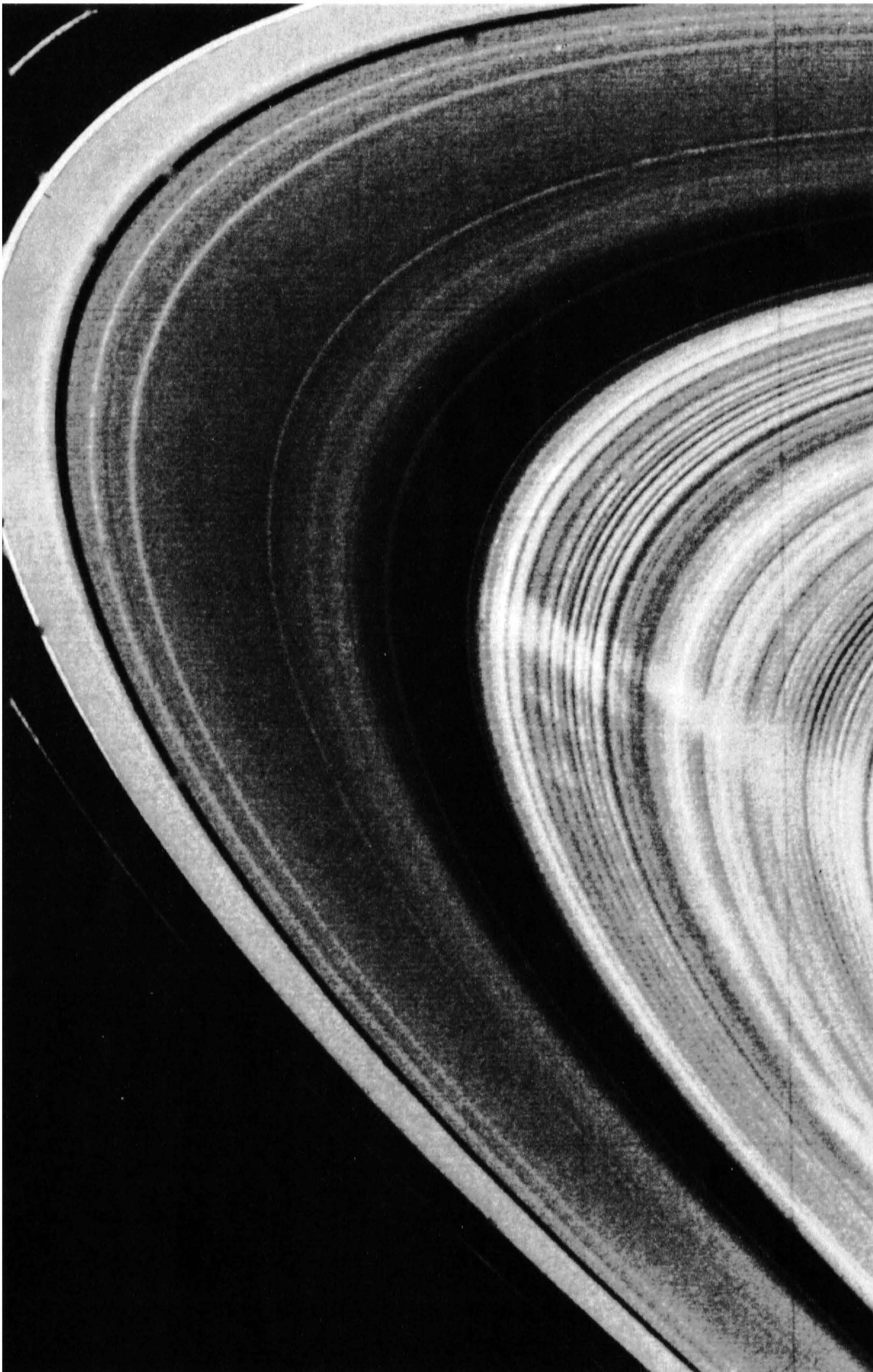
But Saturn is *not* a bust. The JPL pressroom teems with reporters—far more than came for the Jupiter encounter. This space mission has clearly excited the public. Why? For one thing, the flawless performance of this little-spacecraft-that-could is a national pride. Space exploration is something the United States is very good at.

Then again, the pictures coming across the monitors speak directly to the imagination. Not fiery, chaotic, and psychedelic like those of Jupiter, they look cool, ethereal, and from a distance orderly enough to have been drawn with a celestial compass.

"Saturn *is* astronomy to many people," notes Reta Beebe, a mission scientist. "Through even a small telescope, it's the most beautiful thing in the sky."

Right now, to Brad Smith, the leader of Voyager's *(Continued on page 10)*

*The author described what Voyager saw in Jupiter's dazzling realm in the January 1980 GEOGRAPHIC.



The rings: spoked, tilted, and eccentric

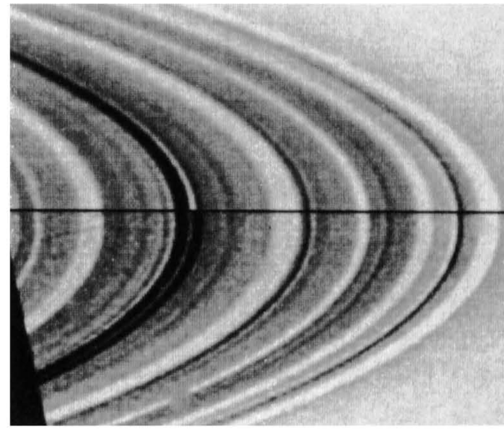
CAROUSEL OF TRILLIONS of particles from smaller than dust to larger than cathedrals courses around Saturn as its ring system. Voyager 1 found it to be full of structure and puzzles—such as spokes, one seen as a light streak **(left)** *across the bright B ring. Spokes may be very fine particles lifted out of the ring plane by electrostatic forces.*

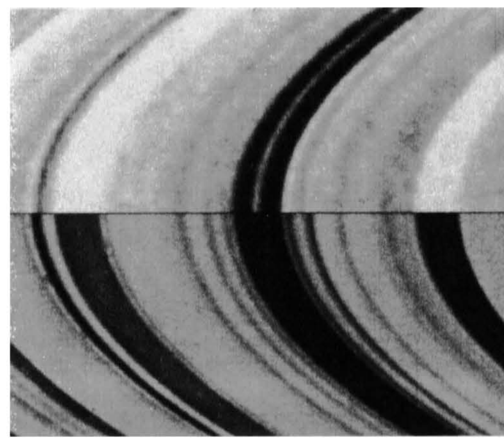
Seen farther out in the grayish part of the A ring are two bright, narrow ringlets close together. Between them is a faint ringlet that begins as white in the upper right-hand corner. When followed counterclockwise, the ringlet turns dark, perhaps because it is somewhat tilted out of the ring plane.

The density of rings can be roughly determined by the play of light upon them. In this composite view **(right, middle)** *the upper, or sunlit, half was taken as Voyager 1 approached. Regions thick with material reflect light and thus appear bright. Regions void of material appear dark. The lower, or shaded, half of the image was taken from beneath the rings. Regions that are bright both above and below indicate particles that reflect light, but also, because of low density, allow some light to pass through. Regions bright from above but dark below indicate density so great that no light can pass through. Regions dark both above and below are void of particles.*

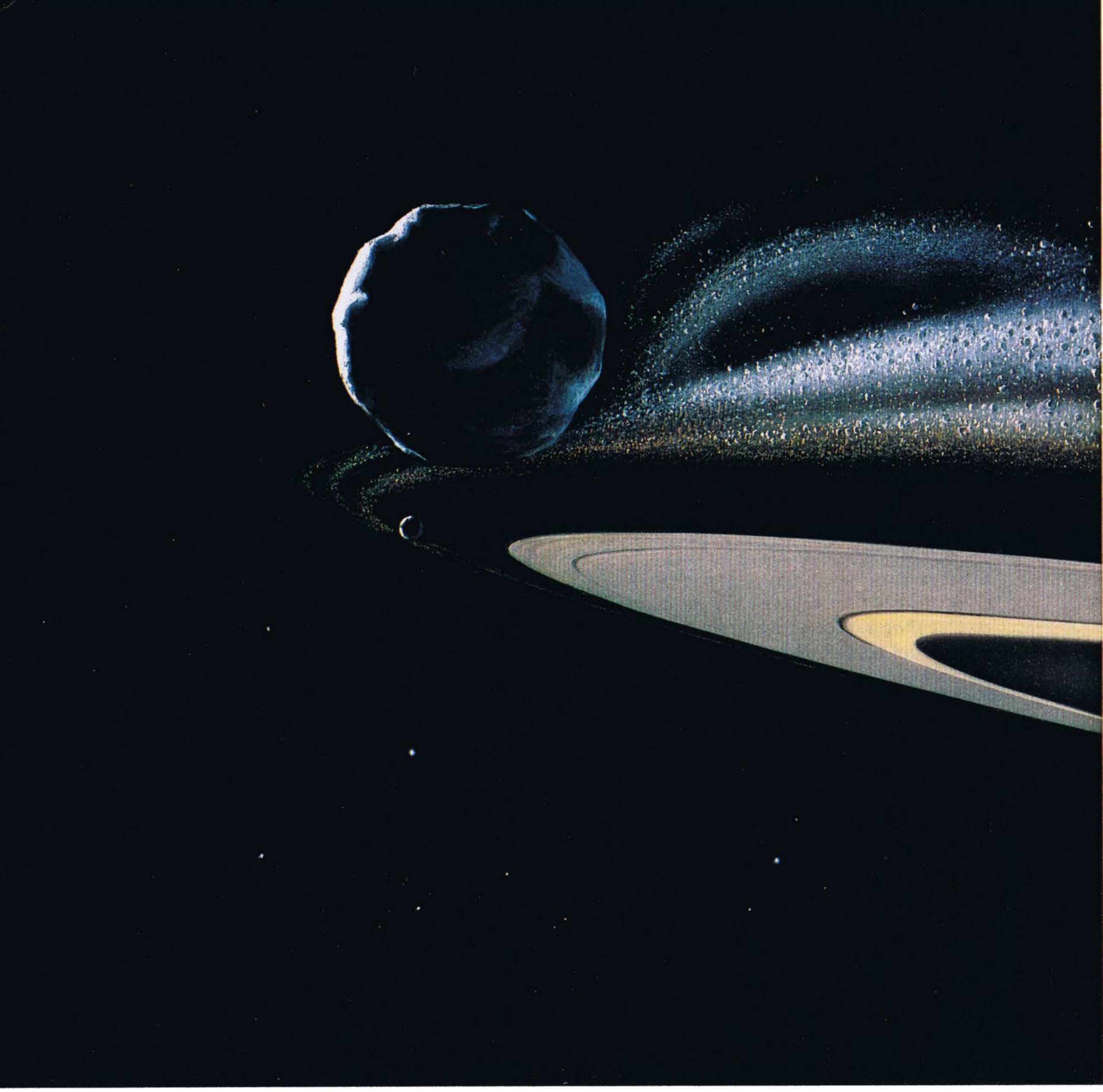
A composite image of two separate sections of the C ring **(right, top)** *shows one ringlet whose track doesn't match up, thus establishing it as an eccentric (out-of-round) ringlet that varies in width. It may be subject to perturbation by small, embedded moonlets.*

The complex structure and features of the rings have turned out to be anything but obvious. As mission scientist Jeffrey Cuzzi **(right)** *points out: "Understanding the structure is going to take a lot more work. It's not something that just clicks into place."*



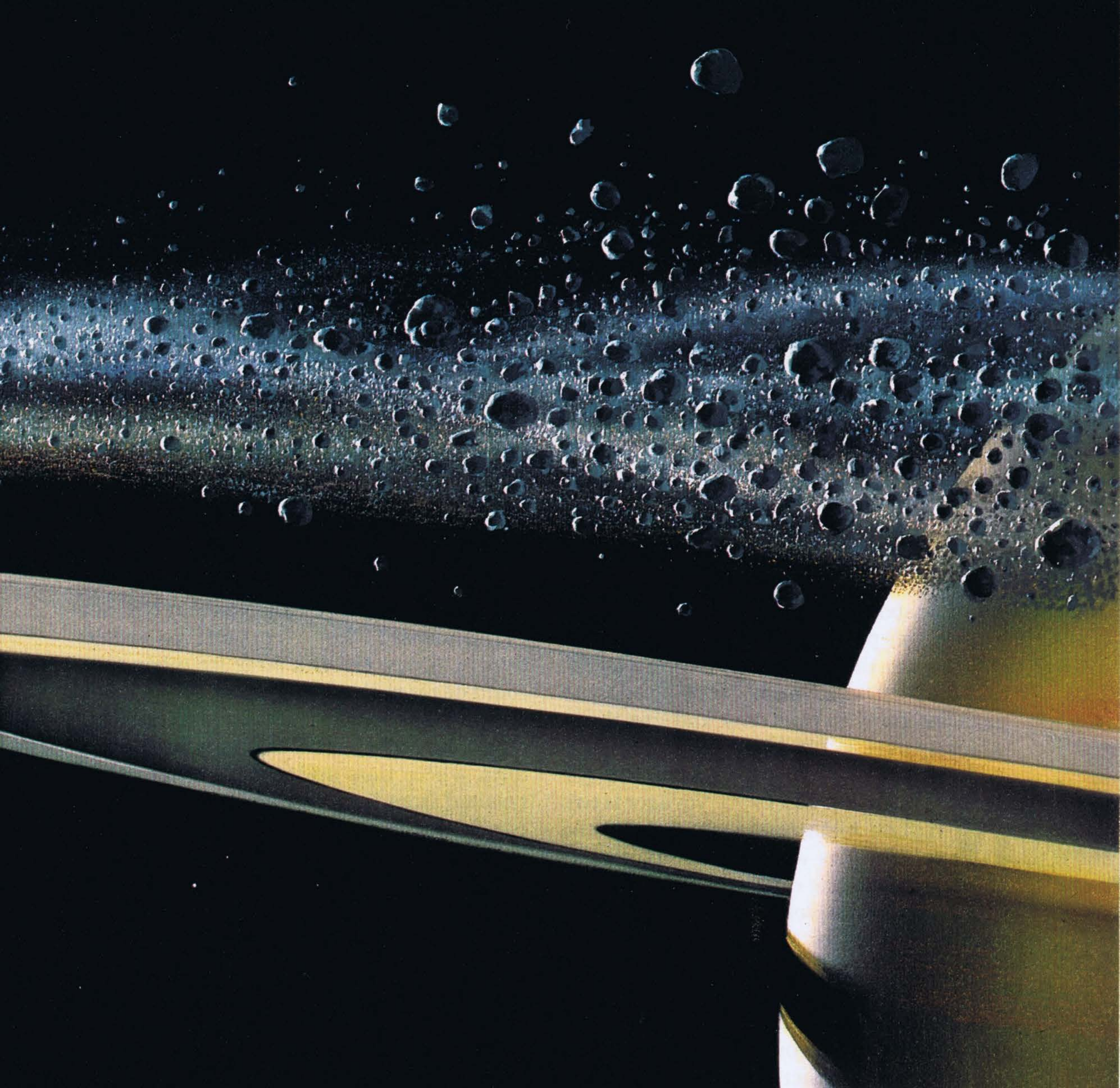


JAMES A. SUGAR

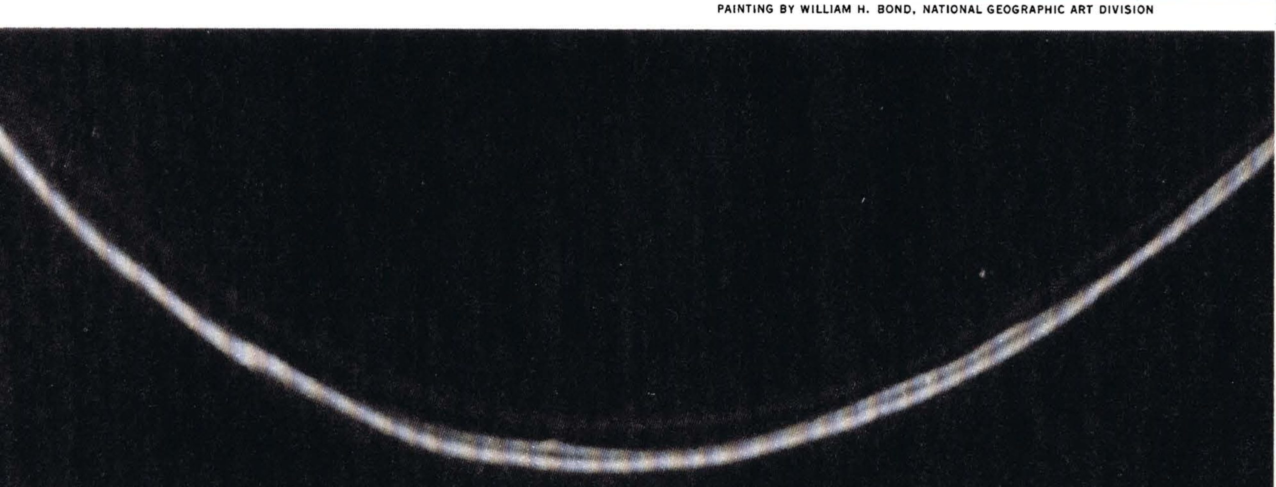


Shepherd moons

IF PACKED snowball fashion, about a fourth of Antarctica's ice could make up the two newly discovered shepherd moons **(above)** *that confine the diffuse and twisted F ring, many of whose particles are microscopic. As seen by Voyager 1* **(right)**, *two of its three strands appear intertwined and kinked, and its material gathered in clumps. Why is the ring so disorderly? The moons' gravity plays a major role, yet their gravity is so weak that astronauts could high jump a hundred meters on them. Both moons have eccentric orbits, as do the ring particles. The inner shepherd, rear, travels faster and repeatedly laps the outer, so the angles and intensities of gravitational pull keep changing. Electromagnetic forces may also play a role. In August 1981, Voyager 2 will take a more detailed look to try to unravel the mystery.*



PAINTING BY WILLIAM H. BOND, NATIONAL GEOGRAPHIC ART DIVISION



imaging team, Saturn is also the most bedeviling thing in the sky. Today he is most baffled by those odd spokes, or fingerlike projections, that are slightly darker than the rings themselves and that stretch across the B ring.

"We've never been confused for so long about anything so obvious," he says, swatting rolled-up paper against his palm. "It's just so damned frustrating professionally. We first saw them three weeks ago, and we still don't have any good ideas."

These spokes emerge from the shaded side of Saturn, sometimes in bursts of five or so, and revolve with the rings. Gradually they fade away. Theoretically each particle that makes up the spokes should behave like a mini-satellite. Those closer to Saturn should be moving much faster than those farther out. The spokes should tear apart. Yet they seem to stay perfectly aligned.

"How do they form in the first place?" asks the frustrated Smith. "How do all those particles know to turn dark and line themselves up over 25,000 kilometers?"

NOVEMBER 11, 1980. Voyager is two million kilometers from Saturn and tonight flies within 4,000 kilometers of Titan. More ring close-ups have come in. Life grows no simpler for Brad Smith.

"The mystery of the rings keeps getting deeper and deeper, until we think it's a bottomless pit," he says at a press briefing. "The thing I least expected to see was an eccentric ring—and we have found two."

He flashes on a picture of one ringlet dramatically fatter on one side of Saturn than on the other (page 7).

Odd things too are happening out at the thin F ring, the one being shepherded by two little moons. Voyager images now show clumps in the F ring. Could these clumps be satellites trying to form? Are they moonlets being eroded? Do gravitational forces from the shepherding satellites focus ring material into odd-shaped regions? The mission scientists are clearly thinking on their feet.

The F ring is close to what astrophysicists call the Roche limit. Inside this limit the gravitational pull from huge Saturn should keep large satellites from forming.

The Roche limit helps explain why Saturn has rings. Most scientists believe that more than 4.6 billion years ago, when Saturn was forming out of the solar nebula, it was much larger. It collapsed suddenly, then began spinning so rapidly that some of its gases and dust were left in a flat disk around its equator. Hot, young Saturn kept this disk much warmer than the minus 185°C (–300°F) temperatures in the rings today. Heavier materials such as metals and silicates either coalesced into Saturn's forming moons or swirled inward to form its deeply buried Earth-size core, which may be molten.

As the planet shrank further, it cooled, as did the ring region. The water vapor that was left there froze, says a leading theorist, Jim Pollack, and the resulting ice crystals gradually accreted into ring particles thought to be no more than a meter in diameter. At some point a phenomenal blast of solar wind blew away any gas that had not yet condensed. The ring particles would thus be the pieces of a large ice moon that could never pull itself together.

There has long been a competing view, however. Perhaps all those particles did not form where they are today. Perhaps they resulted from some catastrophe. The rings could actually be the end product of a moon, suggests mission geologist Gene Shoemaker. They could be a satellite smashed to pieces by another icy body. Or perhaps such a body, a traveling, homeless moon, was torn apart by Saturn's gravity.

However the rings formed, most astronomers believe they have been choreographed ever since by the laws of orbital mechanics, especially the process called resonance.

Through resonance the gravitational effects of Saturn's moons on parts of the rings are greatly magnified. For instance the moon Mimas and the inner edge of the Cassini Division are in resonance. Mimas takes exactly twice as long to orbit Saturn as do certain Cassini particles. This regularity means that these particles meet a slight gravitational tug from Mimas at precisely the same place every other orbit. Over time that extra tug stretches their circular orbits into ellipses. Eons ago Cassini particles thus started to crash into particles in adjacent orbits. Colliding particles were thrown into other parts of the rings. Gradually a large gap was swept out.

Before Voyager such resonances were

thought to be responsible for what little structure the rings had shown. But now the monitors at JPL are showing more structure, not only in the rings but also in the Cassini Division, than any symphony of resonances could explain.

THE NAME Peter Goldreich keeps popping up. Goldreich is not on the Voyager team. He teaches at the nearby California Institute of Technology. But of the minds that probe the dynamics of the solar system, his is among the very best.

Nearly two years ago in his Caltech office he noted: "The rings of Saturn are not going to be that easy." The subject then was Uranus. At least nine very narrow, very peculiar rings had recently been discovered around that planet, the next one out from Saturn. One of these rings is only three kilometers wide. The outermost is eccentric; its width varies from 20 to 100 kilometers.

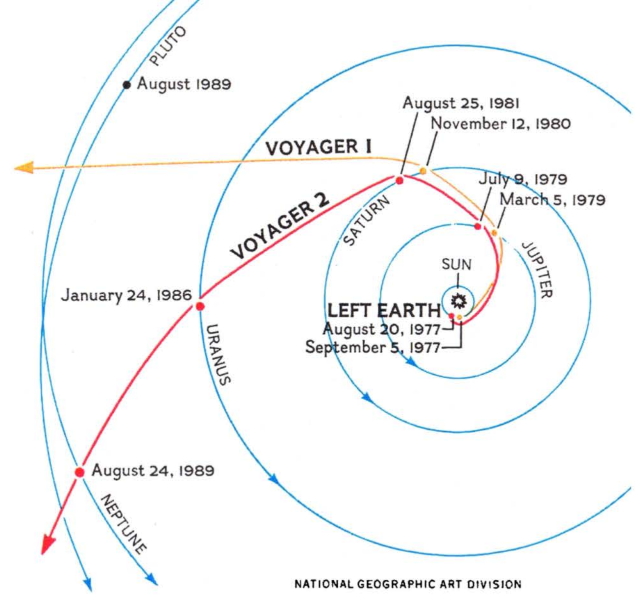
Goldreich and Scott Tremaine had proposed that it was not resonances but rather many little moons, too small to be viewed from Earth, that created Uranus's rings.

"Two satellites orbiting close together can confine small particles in between them into a thin ring," he had explained. "Gravity causes each satellite to repel the particles in its vicinity."

Gravity repel? The explanation is a riddle lover's delight.

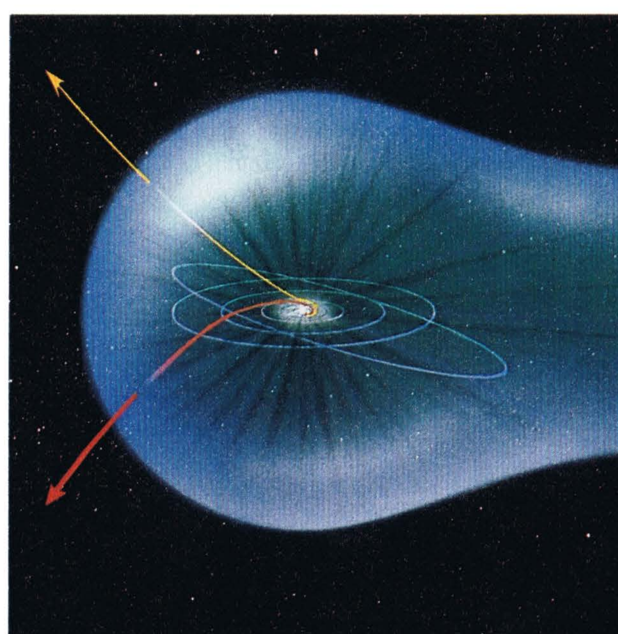
The laws of orbital mechanics dictate that satellites in higher orbits go more slowly than those below because they need less velocity to overcome the pull of gravity from the planet. So if you have two moons with lots of ring particles between them, the inner moon will move faster than the particles, and the outer moon will move more slowly.

Consider the inner moon first. As it nears the slower ring particles, its gravity does indeed tug at them, pulling the particles closer to it and slowing them down. But as the moon passes, its gravity then starts to pull the particles along after it, speeding them up. Because the particles have been pulled closer to the moon, the satellite's gravity has a stronger effect on them after the moon passes than before. So they are accelerated more than they were slowed down. The ring particles get a net energy gain from the inner moon. That energy boosts—



NATIONAL GEOGRAPHIC ART DIVISION

Gravity's crack-the-whip *sends each Voyager on its appointed course. If all goes well, Voyager 2 will use the boost of Saturn's gravity to put it on a trajectory for encounters with Uranus and, finally, Neptune, arriving at its last planetary rendezvous 12 years and 4 days after launch.*



SUSAN SANFORD, NATIONAL GEOGRAPHIC ART DIVISION

At the outer limits *of the solar system—the heliopause, where the solar wind can no longer expand against the pressure of interstellar gases—Voyagers 1 (yellow) and 2 (red) will make some of their last reports—at least to Earth.*

or repels—the particles into a higher orbit.

The reverse is true with the outer moon. Ring particles are overtaking it. So as they near the moon, it speeds them up and draws them closer. As they pass, it pulls them back, slowing them down. The particles are closer to the moon when they start being decelerated. So they have a net energy loss to the moon. Losing energy, they fall into a lower orbit. The moon pushes them in.

Even though the moons themselves gain and lose energy interacting with the particles, resonances with other moons could lock them in their orbits.

Many considered such gravitational gamesmanship unconvincing. "It's a terrible thing to have to make a model when you need nine or so little satellites that can't be seen," Goldreich had conceded, "but I have no doubt that it's correct."

Suddenly Goldreich seems like a prophet. Saturn's shepherding moons act just like the moonlets of Uranus in his model. Could Saturn's rings have countless perturbing, distorting, invisible moons shepherding its ringlets as well?

NOVEMBER 12, 1980. The rings continue to confound. "We thought we had seen all there was to see," Brad Smith tells the press. "But in this strange world of Saturn's rings, the bizarre has become commonplace. When we looked at the F ring today, this is what we saw."

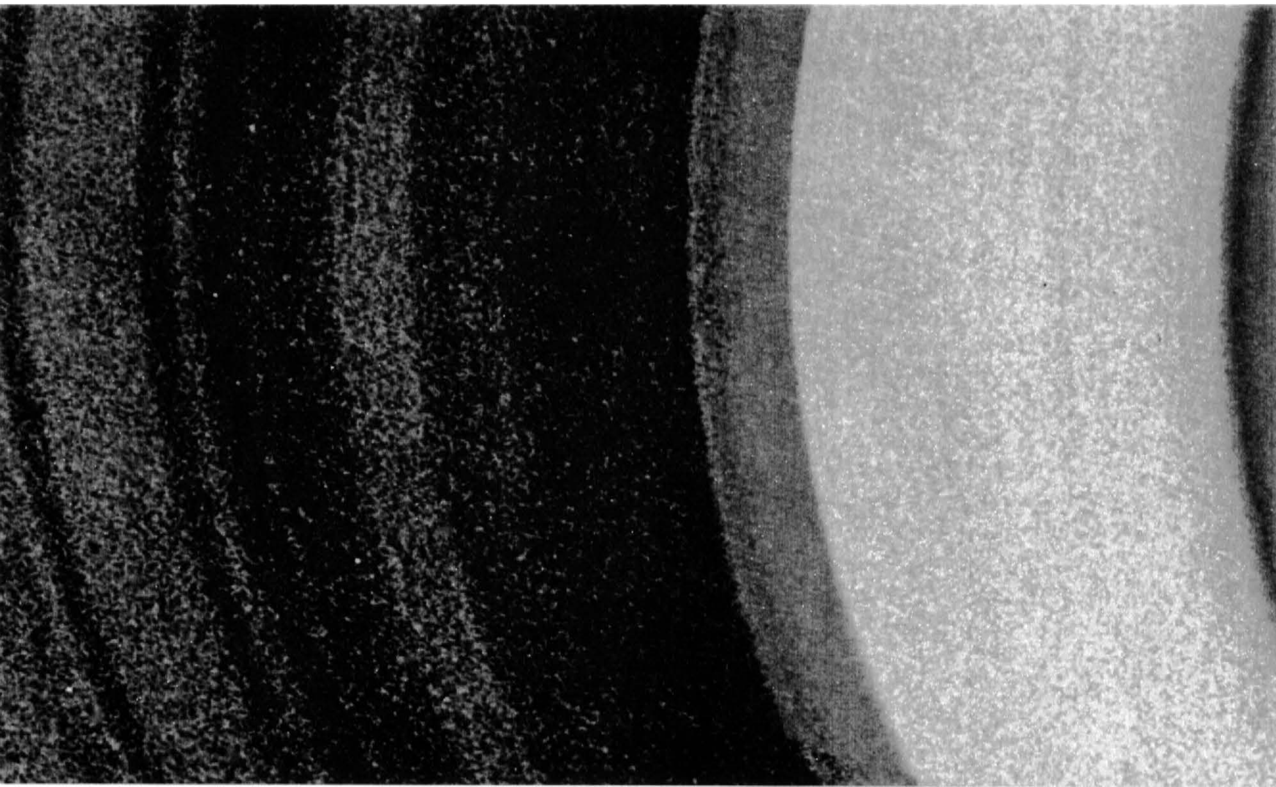
What Smith shows is a picture of the F ring split into three strands—two of them appear intertwined. They resemble a DNA double helix. Someone jokes that Voyager has discovered life at Saturn. Smith notes that there are also kinks in the strands.

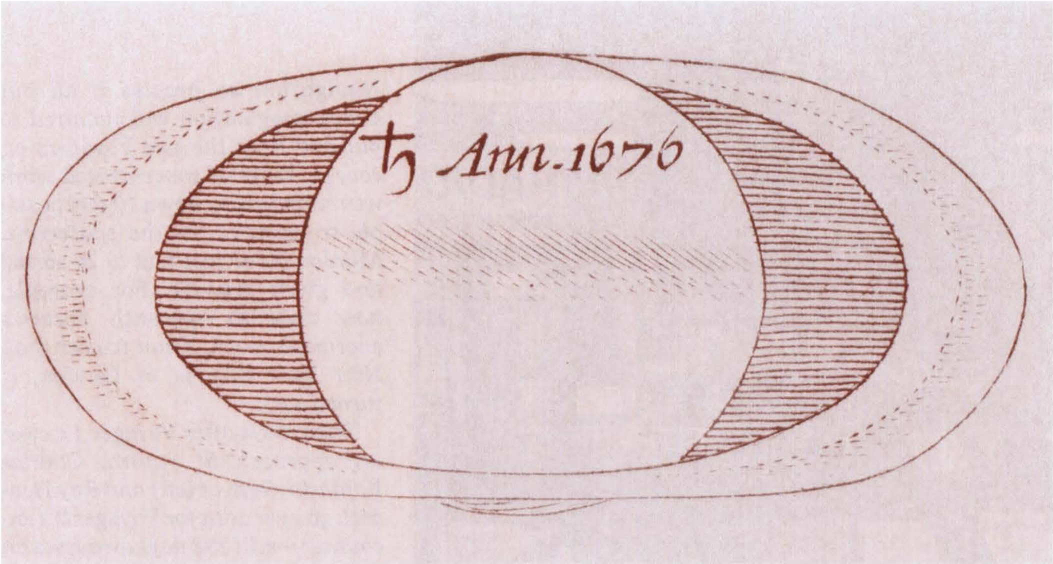
"Braiding defies the laws of orbital mechanics for several reasons," he says. "But obviously these rings are doing the right thing. I guess we just don't understand the laws very well."

Attention is about to be drawn away from the rings. Overnight the closest images of Titan have come in. Faces are long. Clouds totally veil the surface. The Titan story will not be told in pictures. But today begins a dizzying series of closest encounters with Saturn's other named moons.

Mimas, Enceladus, Tethys, Dione, Rhea. Not to mention Hyperion, Iapetus, and Phoebe. "Too many moons," grumbles moon specialist Larry Soderblom. Until this week most of Saturn's named moons were merely points of light through a telescope. Project scientists cannot even agree on pronunciation. Some say Mee-mas, some say My-mas. Some make Enceladus (En-SELL-a-dus) sound like a Mexican dish.

These bodies are much smaller than Earth's and Jupiter's large moons, or their





COURTESY U. S. NAVAL OBSERVATORY

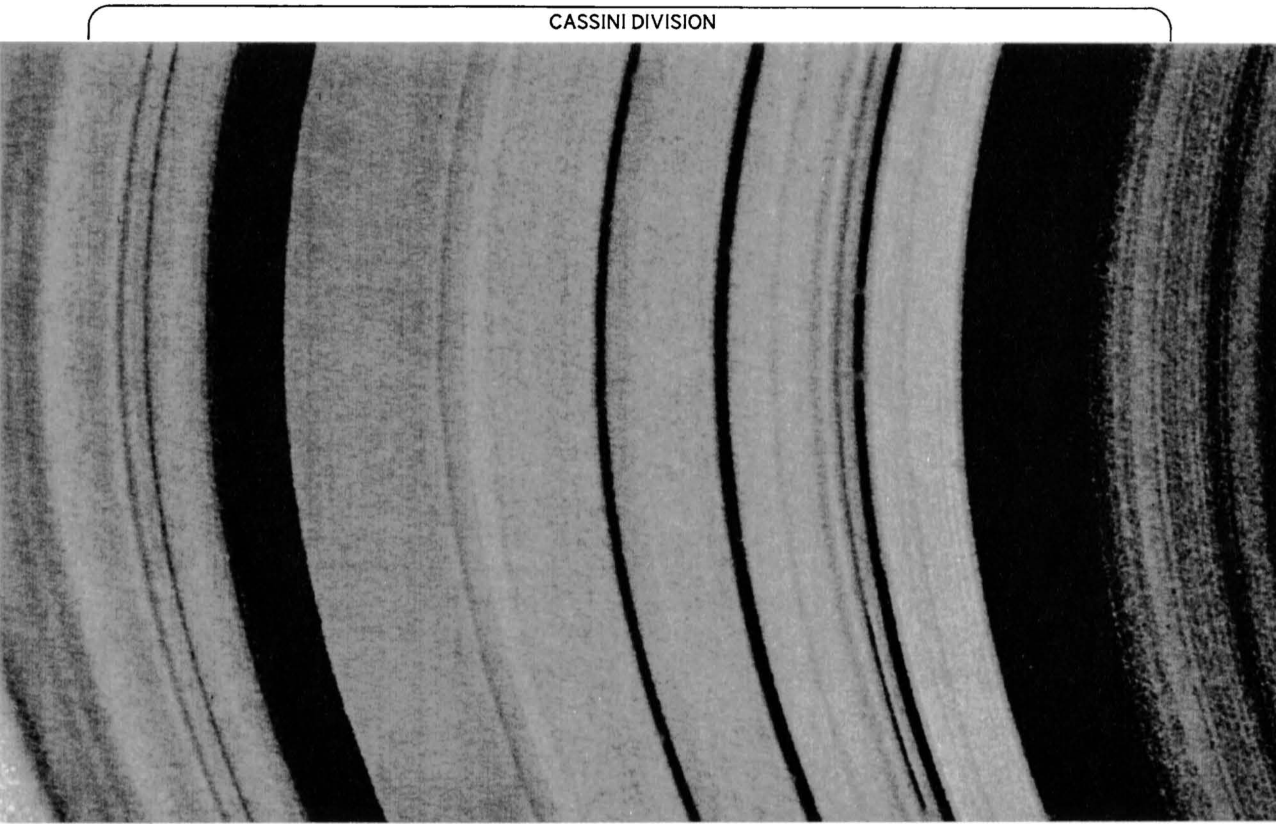
A dangerous reef in the rings

*THE 15-GENERATION GAP: For centuries after Franco-Italian astronomer Jean Dominique Cassini discovered what seemed to be a gap in Saturn's rings and sketched it **(above)**, the Cassini Division was thought to be a clear zone. A detail of a Voyager image taken from beneath the rings **(below)** proved quite otherwise.*

One trajectory considered—and rejected—for an earlier spacecraft to Saturn, the less complex Pioneer 11, would have taken it through the Cassini Division.

Pioneer would have likely discovered that the division is no gap—and discovered it in the most unplanned, unpleasant, and final way.

CASSINI DIVISION



***Navigation so precise** it all but defies imagination was required to put and keep the two Voyagers on course. Years of concentrated work went into boiling down 10,000 possible trajectories for the spacecraft. Mission objectives had to be sorted and given priority: For example, how close to approach Saturn's enormous moon, Titan (closer than New York City is to London, it turned out).*

*Three days after Voyager 1's closest approach to Saturn, Charles Kohlhase (**left**, at left) and Ray Heacock go over data for Voyager 2's encounter—still 283 days away, yet an immediate and pressing concern.*

*As a navigation aid, computer-generated images chart the region where Voyager 2 will pass between tilted Uranus (**right**) and its moon Miranda. Eventually, the craft will reach Neptune and dive over its north pole just 7,500 kilometers off the surface.*

brother satellite Titan, yet larger than most asteroids and the tiny moons around Mars, Jupiter, or Saturn.

They should be made from roughly the same material—dust and ices—as comets. They should be too small to have much of the radioactive rocky material that in larger bodies heats up the interior and generates geologic processes such as volcanism. These watery moons should have frozen fast soon after forming. They should be heavily pocked with craters, the scars of countless random collisions with celestial debris. There is no reason to suspect they are anything but big dirty snowballs.

Voyager will not come close enough to Hyperion and Iapetus to reveal much. It will not even photograph Phoebe, the farthest out. Phoebe has long been known to travel in the opposite direction from Saturn's other moons. It is most likely debris captured by Saturn's gravity as it passed by.

Iapetus is perplexing. Even from Earth, it shows two faces. One side is five times brighter than the other. No one really knows why, and Voyager 1 will not see it well.

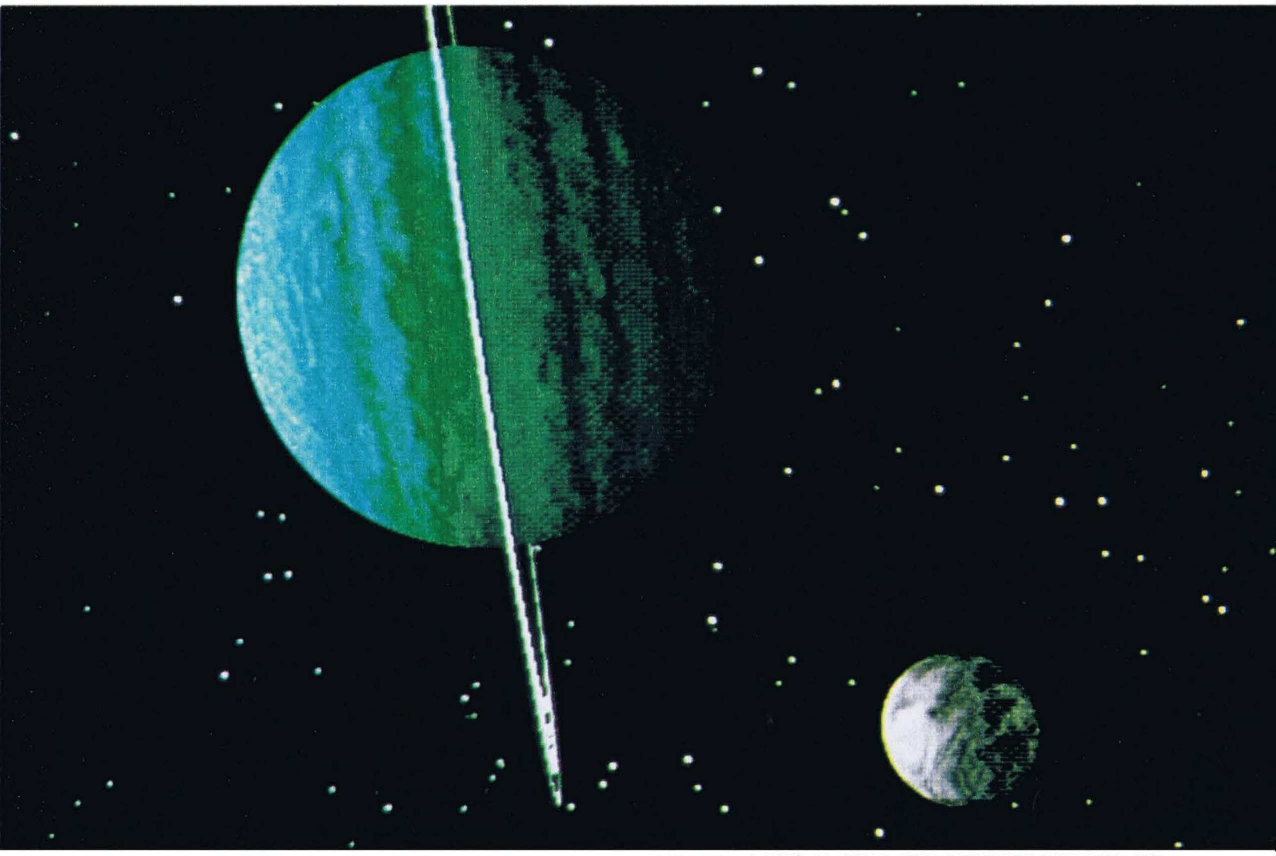
But Voyager 1 has begun seeing some startling features on the inner moons.

Mimas, the innermost, looks the most like the bland snowballs everyone expected, except for an enormous impact crater (pages 16-17). Its walls are five kilometers deep, its diameter a third that of the moon. It is among the largest craters, relative to the size of the body hit, ever seen. Mimas came very close to being blown apart.

Like the other moons, Mimas is so cold that ice on its surface is as rigid as rock. "It's got about all the craters you can make," says Gene Shoemaker. "If you make any new craters on Mimas, you'll erase old ones."

This cratering has "fluffed up" or "gardened" the surface to a depth of at least several kilometers. So walking on Mimas would be a little like walking on a large snow cone, with many ice chunks, some larger than a house, sticking up from the rubble.

Farther out and much larger is Tethys. A great branching trench 65 kilometers wide stretches nearly from one end of this well



JAMES A. SUGAR (LEFT); COURTESY CHARLES KOHLHASE AND JAMES BLINN, NASA

cratered, 1,050-kilometer-diameter moon to the other (page 26). The valley looks too grand to be an impact fracture. It appears to have been created from within. Perhaps the stress of Tethys's freezing and expanding interior cracked the surface of the moon. Perhaps internal geologic churning caused the trench. Yet Tethys has a density close to pure water ice. How could a body with so little rock have been geologically active?

Tethys is extremely bright, yet not as bright as its astounding neighbor Enceladus. Enceladus reflects nearly 100 percent of the light striking it. Our moon, by contrast, reflects 11 percent.

Enceladus also seems to be strikingly smooth. Voyager observes no craters. Could some geologic process on Enceladus (pages 30-31) still be actively erasing or swallowing its craters? Enceladus could well be geologically alive.

Strange white wispy markings streak the next two moons out, Dione and Rhea, suggesting that something once blew out of their interiors.

Impact craters, formed very early in the solar system's history, blanket much of Rhea's surface, as they do that of Mimas. Yet some areas show less cratering. They apparently have been resurfaced.

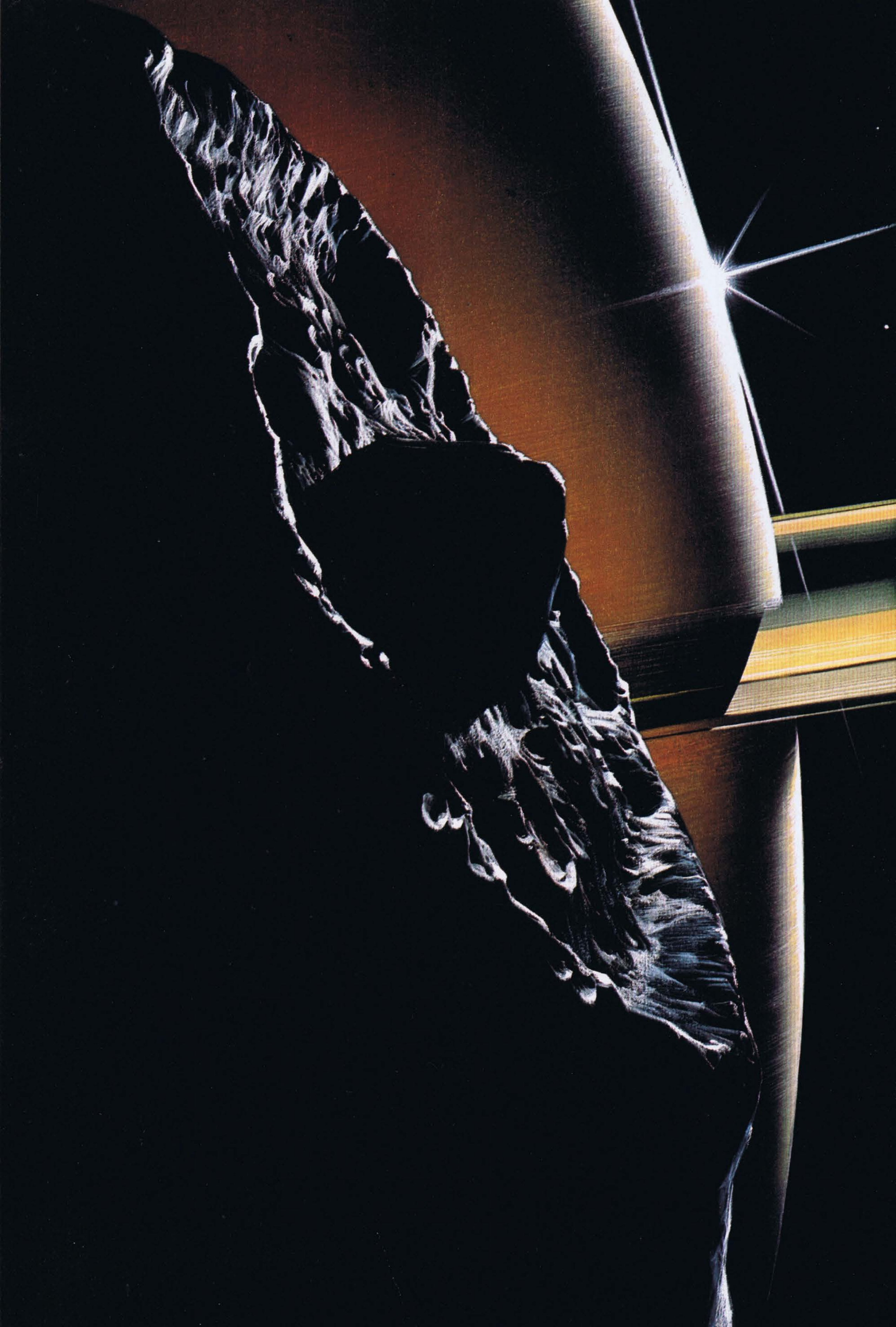
Dione is in places as heavily cratered as Rhea, but it has a lot of younger terrain. As Larry Soderblom puts it, "Sometime, probably in its first half billion years, Dione's insides gushed out across its surface."

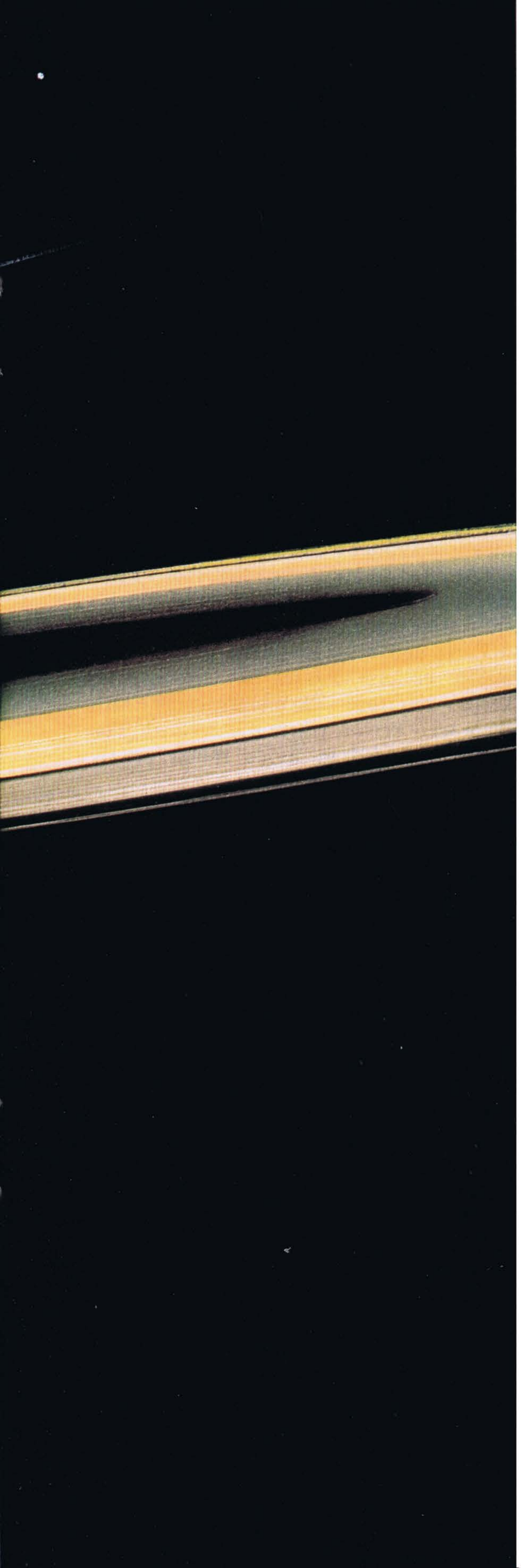
Mystery still shrouds the cloud-covered Titan. Titan will soon demonstrate, however, that Voyager can do more than take stunning pictures.

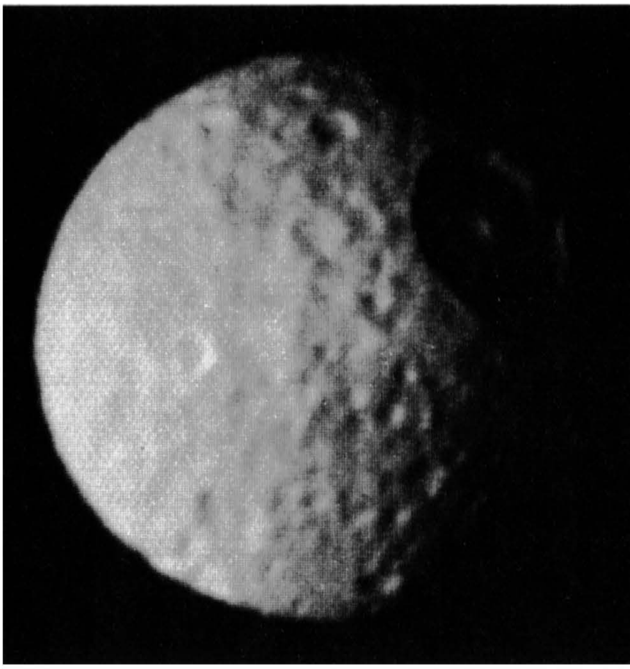
NOVEMBER 13, 1980. Scientist Rudy Hanel, leader of the NASA infrared spectroscopy and radiometry team, is ebullient.

"The rings may belong to the picture people, but Titan belongs to us!" he says.

Hanel's heat-analyzing instrument and data from the radio-science team have revealed that Titan's atmosphere is largely nitrogen, like Earth's. Not the widely





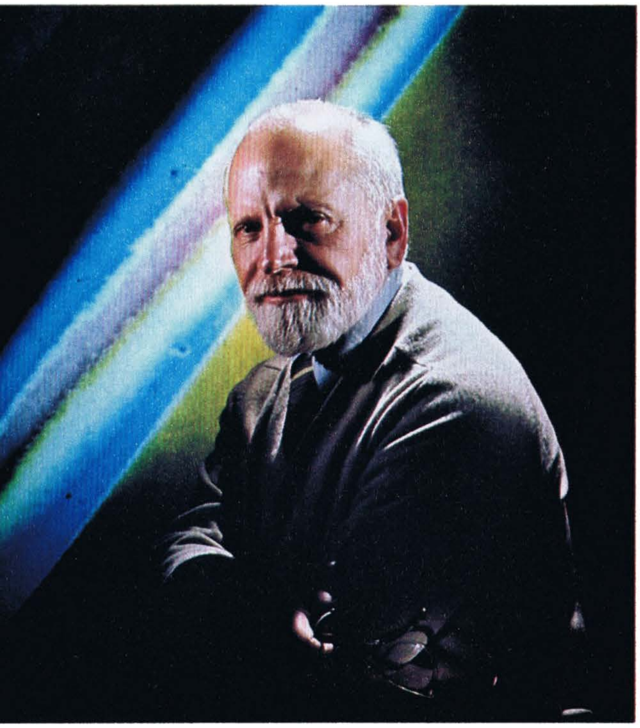


Mimas: a satellite nearly shattered

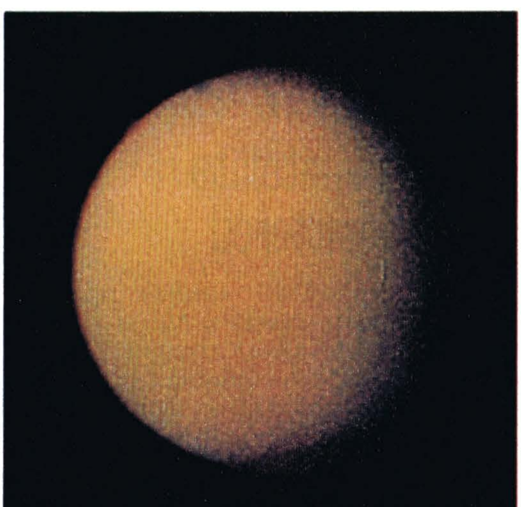
"IS IT THE ENGINE?" someone asked when this view (**above**) *of Mimas was first shown. The "engine," a crater 130 kilometers across, remains from a collision, probably with another moon, that nearly blew Mimas apart perhaps four billion years ago. Grooves on the satellite's opposite side may have been caused by the tremendous stresses of impact on a body whose gravity is only five thousandths that of Earth.*

The impact created steep crater walls, but a natural process called isostatic rebound formed a central peak (painting, ***left****) that rises six kilometers from the crater floor. The effect would not be greater if Delaware were rolled into a ball and Mount Everest dropped on it.*

PAINTING (LEFT) BY WILLIAM H. BOND



SISSE BRIMBERG AND GARRY E. HUNT



***Titan showed a blank face** as Voyager 1 neared. The only features visible **(above)** were a haze, a darkening of the northern hemisphere, and an even darker polar hood. The radio team and the infrared team, the latter led by Rudolf Hanel **(top)**, probed Titan to its surface and found: temperature, 93° Kelvin (minus 292°F); atmospheric pressure, 1.6 times Earth's; main gas constituent, nitrogen; diameter, 5,140 kilometers—demoting it to second place behind Jupiter's Ganymede as the solar system's largest moon.*

suspected methane. Methane is only a minor constituent, as water vapor is on Earth.

It is announced today that Titan's atmosphere is at least as dense as Earth's. It includes hydrogen cyanide. That news would not stop presses. But to biologists it is significant: Hydrogen cyanide is a critical building block for the more complex molecules of life.

The temperature at cloud tops is far too cold for life. But some scientists speculate that Titan's thick clouds could trap enough heat down below to make life imaginable.

There are not that many atmospheres in the solar system. Titan has one because it is massive enough to hold onto its gases gravitationally. Also, its temperatures are so cold that gas molecules do not have the energy to escape its grasp, as happened on the large moons of Jupiter when they formed.

"At Titan we may have a snapshot—a frozen record of the composition of Earth's early atmosphere," says Hanel.

Earth and Titan are different today primarily because Titan's low temperature keeps water frozen. On much warmer Earth there were oceans where life evolved. The oxygen released by living things utterly changed our planet's character.

Titan might have known warmer days as well. Gaseous ammonia in its early atmosphere may have trapped enough heat to permit liquid ammonia or even water to run across the moon's surface. Life could have begun and then frozen out.

"Presumably the fossils of chemical evolution are sitting out there waiting to be found," says mission astronomer Toby Owen. "You just need a long enough drill to get through the ice."

WHILE TITAN has stolen this day's show, the ring people are also excited. Voyager has flown past Saturn and is now taking pictures looking back. The mysterious dark spokes have suddenly turned bright. That means the spoke particles must be scattering sunlight forward toward Voyager's outbound eyes much more strongly than they had reflected it back toward the spacecraft as it approached. "That property is characteristic of very small particles," explains chief project scientist Ed Stone.

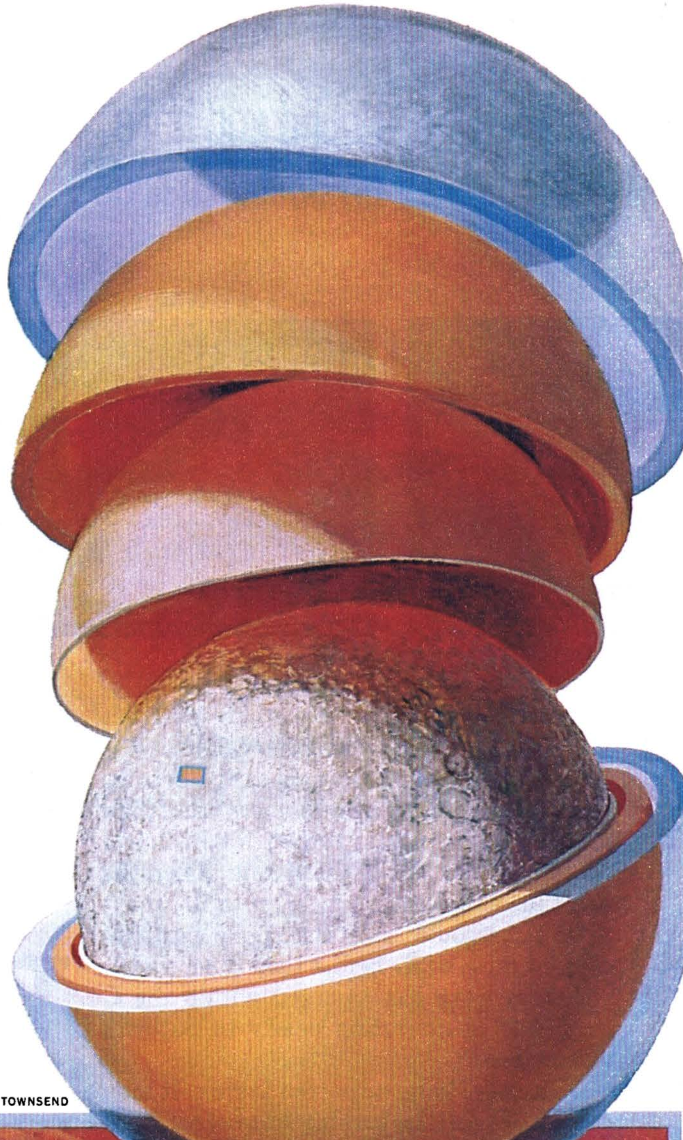
Looking back at the F ring, it too appears

Titan: a gas-wrapped moon

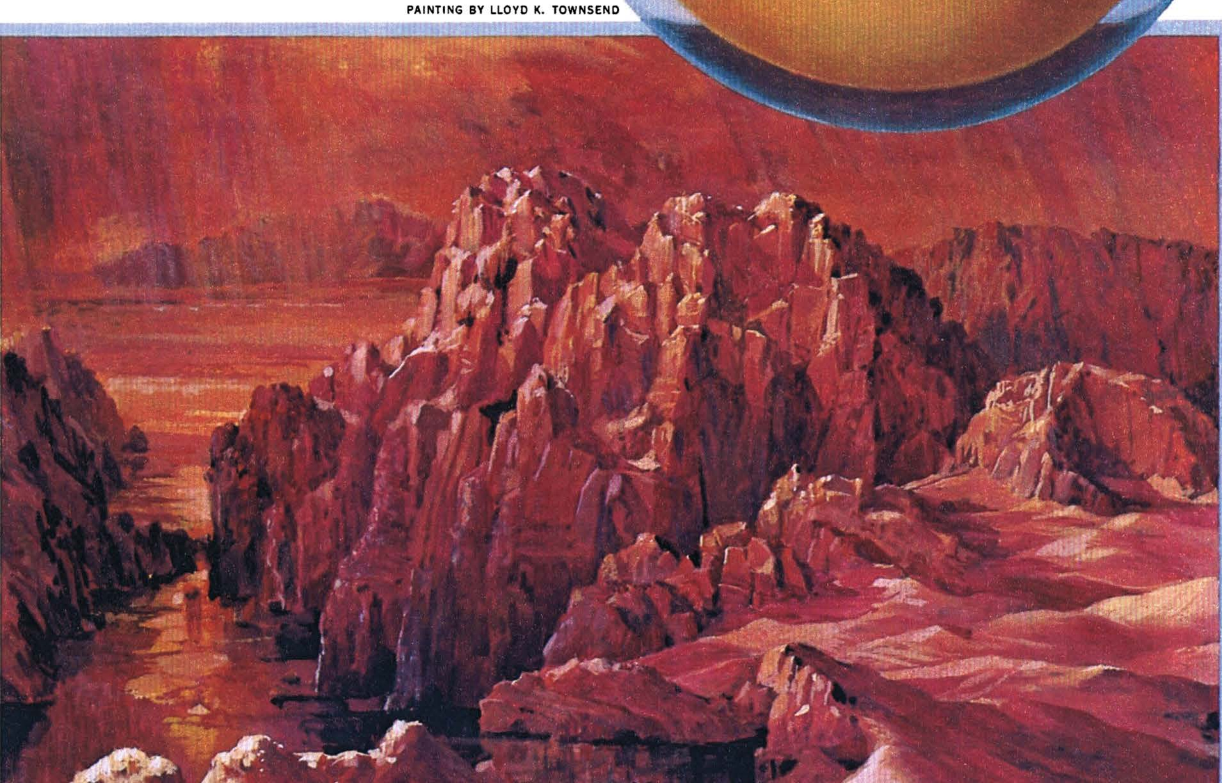
*EXPLODED VIEW shows Titan's layered atmosphere (**right**). Outermost layer shown is a bluish translucent haze of organic (carbon-based) compounds. Within the haze and directly above the north pole of the planet-size moon is a hood of concentrated compounds, present perhaps only during the $7\frac{1}{2}$-year winter.*

Below a relatively clear zone lies a thick layer of smog, again organic compounds, but of larger particles and characteristically red. Under that is a layer of methane clouds and yet larger organic particles.

*The topography of Titan's surface can only be guessed at. But since methane likely plays the same role as does water on Earth—it can be solid, liquid, or gaseous—this scene (**below**) is a reasonable conjecture. Fine methane sleet falls out of a perpetually cloudy sky. Jagged methane escarpments rise from a methane lake under a weak, obscured sun where full daylight may be comparable to full moonlight on Earth.*

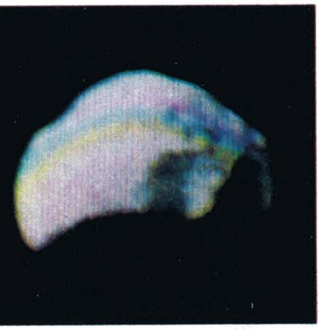


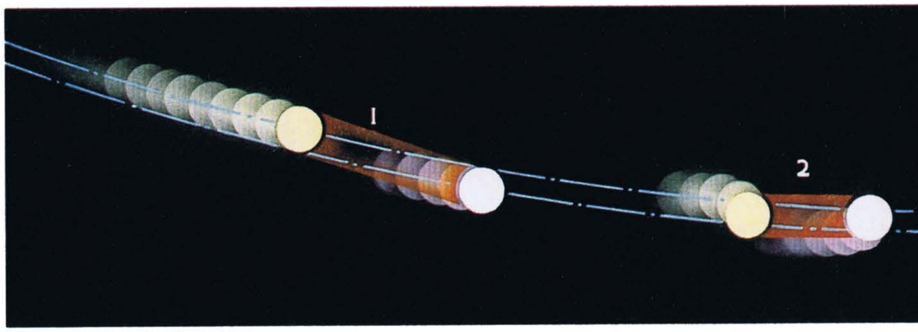
PAINTING BY LLOYD K. TOWNSEND



Hound and hare on Saturn's track

TO CATCH UP but never pass is a role each of the co-orbital moons plays in turn. When Voyager 1 flew by, the somewhat smaller and more ragged-looking moon ***(below, far left)*** *trailed its more regular companion* ***(far right)****. Colored stripes on the trailing moon are successive filter images of the F ring's*





brighter. Both must have many particles about the size of wavelengths of light.

Such small particles can easily become electrically charged by influences other than gravity. Electrostatic forces, for instance, could lift them out of the B ring. Then the force lines of Saturn's huge, rotating magnetic field could keep the spoke particles aligned for a while before they shear apart.

A faint ring has emerged within the C ring, and is extending nearly to Saturn's atmosphere.

This is the long-suspected D ring. It may consist of particles leaking from other rings and spiraling toward Saturn. It could be scattered chunks too large to be pulled in. It could be both. Or neither.

Close-ups of one of the co-orbiting moons have come in. It looks like a tooth. This odd shape leads scientists to speculate that these two moons were once one. An impact blasted it in two. That could explain why their orbits are so close together.

But how do they avoid colliding? They behave somewhat like the shepherd moons.

"Think of the moons as runners on a track," suggests mission astronomer Rich Terrile. "The runner, or moon, in the inner lane is slowly overtaking the one in the outer lane because celestial mechanics say that the closer in you are, the faster you go.

"Now as the inner runner catches up, he starts to feel a gravitational tug from the outer runner—he gets energy from him. As he absorbs this energy, he gets boosted into a higher orbit and slows down.

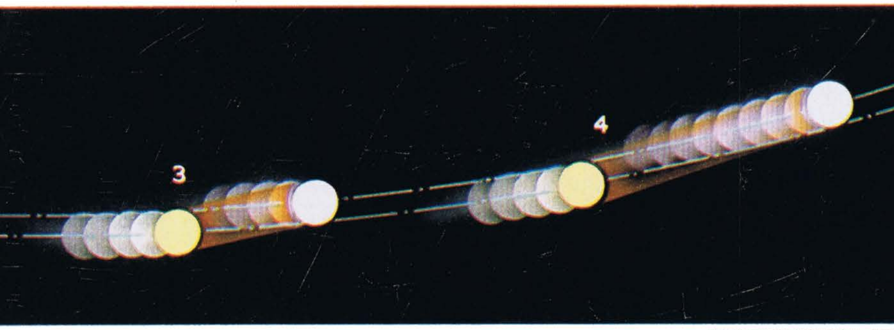
"The outer runner meanwhile has lost energy, and he falls into a lower orbit. He now goes faster and eventually laps the other runner, and the orbit exchange starts all over again."

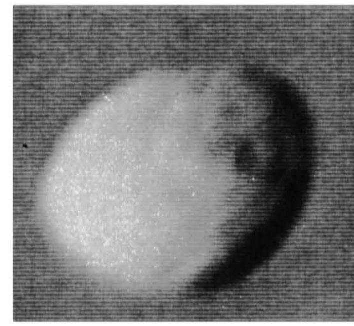
THE RINGS AND MOONS have attracted so much attention that Saturn itself seems almost forgotten.

Compared to Jupiter, Saturn looks unexciting. The two planets are supposed to be very similar—giant gas balls of hydrogen and helium with hot interiors that provide much of the heat that drives their winds and weather. (See the special supplement distributed with this issue for a Voyager 1 view of Saturn and for a chart of our solar system.)

Why then does Saturn appear so bland? A thick haze may enwrap the ringed planet. And that haze could be obscuring cloud tops that are indeed as vividly colored as the cloud tops on Jupiter. Or else the convective currents from Saturn's seething interior may mix the colorful trace constituents in its clouds better.

Voyager close-ups are confirming that Saturn does have a smaller version of Jupiter's Great Red Spot. It also has white ovals and bands of lighter and darker clouds like Jupiter's. Both planets have strong jet streams racing around their equators. On Jupiter, upward from about ten degrees of *shadow. The moons' gravitational minuet is shown in the diagram below.* **1** *The trailing (yellow) moon travels faster because of its slightly nearer (to Saturn) orbit and approaches the leading moon.* **2** *As the moons close, gravitational force energizes the trailing moon, throwing it into farther orbit while dragging the leading moon into nearer orbit.* **3** *Now in the nearer orbit, the leading moon travels faster.* **4** *The leading moon pulls away, and the gap between them widens. After about four years, the leading moon (having become the trailing moon) catches up and the pattern repeats.*





PAINTING BY WILLIAM H. BOND

latitude, other jets appear, each going alternately in opposite directions. Saturn's equatorial jet stream, however, is three times broader. Its winds are blowing more than three times stronger—a thousand miles an hour. Reverse jet streams appear only at far higher latitudes.

Why the difference? Is it because Saturn is tilted and so, like Earth, has seasons? Could the shading of the rings play a role?

Being farther out, Saturn gets only a fourth the solar energy that Jupiter receives. At Jupiter the solar heat striking the atmosphere is equal to the internal heat coming up. At more distant Saturn internal heating dominates. The upwelling of this heat may generate the much stronger surface winds. In any event, both planets are a theorist's delight.

"We have this paradox of bodies that are somewhat like stars inside, but have Earth-like weather on the outside," says mission meteorologist Garry Hunt.

NOVEMBER 17, 1980. Voyager 1 is on its way to a rendezvous a decade from now with the outer edges of the solar system, where the solar wind's influence ends. "We've had a great ride," says chief scientist Ed Stone. "It's been so smooth, it's hard to appreciate how much work went into it. Building the spacecraft was the work of thousands; flying it was the work of hundreds." Planning where Voyager would fly took years of studying just where each moon and planet would be when. Ten thousand different trajectories were considered during the research period.

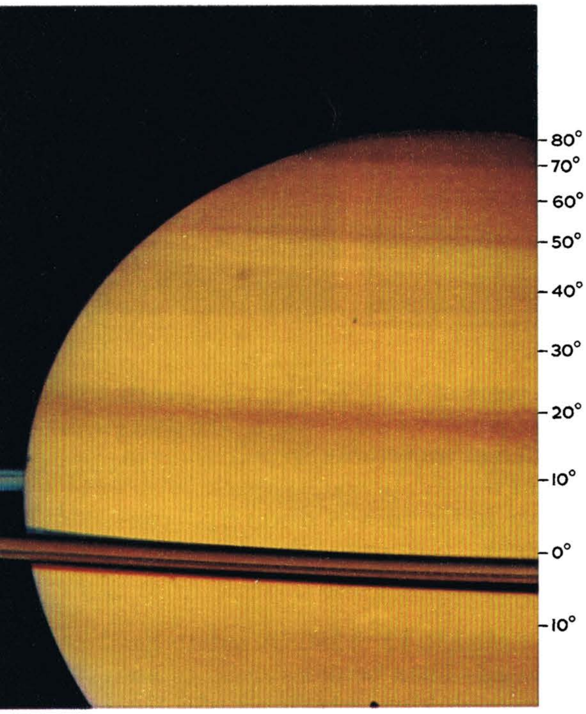
"We are in the rush of discovery," concludes Stone. "Next comes the understanding, which may take years."

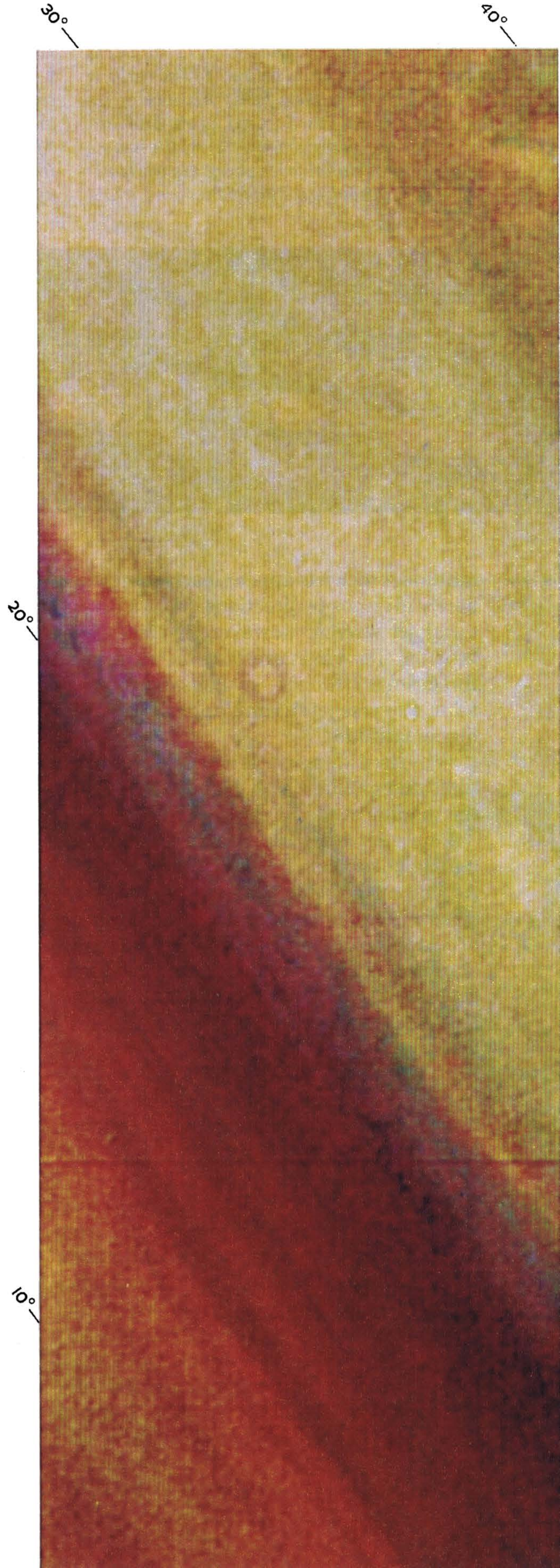
DECEMBER 12, 1980. A month has passed. Titan becomes easier to understand. Mission radio scientist Von Eshleman announces in San Francisco that his team's experiment now shows Titan's atmosphere to be 4.6 times denser than Earth's, and its surface to be 93° Kelvin, or minus 292°F. Too cold for life. But cold enough for methane to liquefy. Titan is right on the edge of having large amounts—oceans, perhaps—of liquid methane.

"Titan may be the only other place in the solar system that has liquid on its surface," says Toby Owen. He believes there are at least lakes of methane.

Methane in Titan's nitrogen atmosphere might well rain or snow out. So will fine particles of other hydrocarbons—what we call smog. "If the surface is solid, there could be four and a half billion years' worth of smog snow, maybe a kilometer deep, covering the moon," says Jim Pollack.

"A few degrees could make a very big difference on Titan," suggests Eshleman. The surface might differ from pole to equator. One region could melt in summer and then

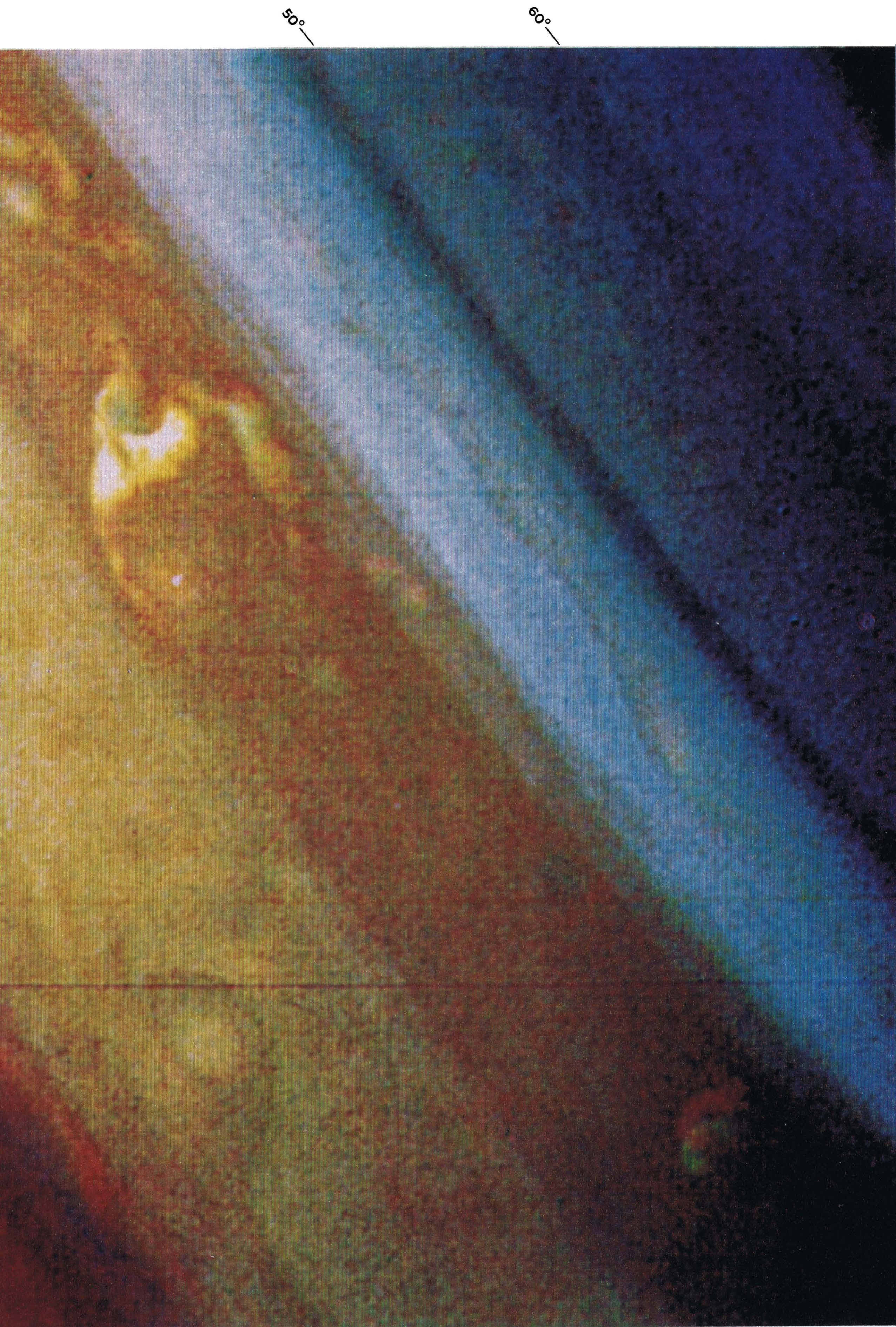




The atmosphere: storm beneath the calm

BLAND AS BUTTERSCOTCH, or so Saturn's atmosphere, composed mainly of hydrogen and helium, appeared from a distance in true color ***(above)****. When resolved into detail by imaging enhancement* ***(right)****, it resembles turbulent Jupiter's.*

Unlike Jupiter's atmosphere, reversals in wind directions do not coincide with the junctures of dark belts and light zones. Saturn's equatorial wind speeds are three times those on Jupiter, or ten times hurricane-force winds on Earth. Whether the sombrero effect of ring shadow or seasonal variations play significant roles in atmospheric circulation is not yet clear to mission scientists.


50°
60°

freeze 15 Earth years later, when the Titan winter arrives.

If there are lakes or oceans, the falling smog snow would make them sludgy. "There should be some very interesting chemistry going on," says Owen.

JANUARY 6, 1981. Over catfish and crab fingers in a Baton Rouge restaurant, Voyager's geologists are trying to decide what to say in their preliminary science report. This impromptu dinner is a break from a NASA planetary-geology meeting. The subject is moons.

Rich Terrile, one of the younger team members, is being grilled across the table about his ideas on Enceladus. There has been speculation that Enceladus could be caught in a tidal tug-of-war between Saturn and Dione. This tugging could be heating Enceladus's interior. The moon could be like a big drop of water coated with an ice crust, explaining why Enceladus is smooth. Like a glacier, the moon's thin crust would be mobile enough to fill in craters.

Terrile and another Voyager scientist, Al Cook, had noted earlier that Enceladus is at the brightest point in the outermost E ring. Terrile now is arguing that Earth-based infrared measurements indicate that the broad and dim E ring has mostly small particles. Terrile and Cook think that those particles could be coming off Enceladus.

"One meteorite puncturing the surface every thousand, or even ten thousand, years could spray out enough ice crystals to supply the E ring," proposes Terrile. Ice volcanoes are also possible. The ring particles that either would produce could be coating Enceladus and neighboring Tethys. That coating might explain why both moons are exceptionally bright.

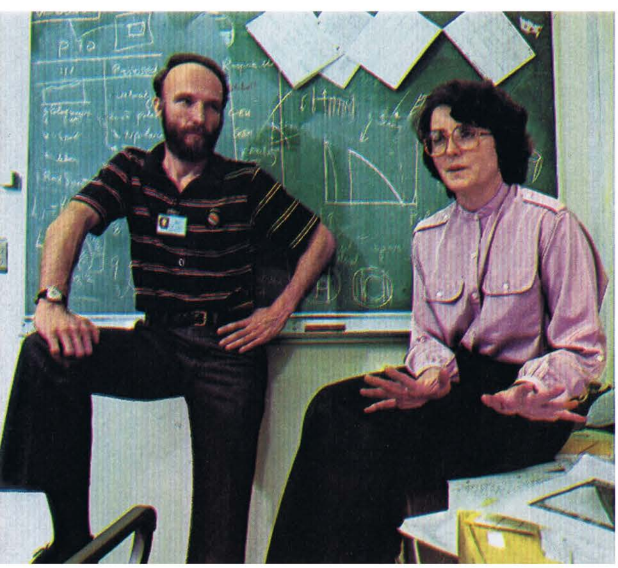
"Nonsense!"—and worse—argue some of Terrile's colleagues. Intuitively suspicious, they question his calculations. He defends his ideas adroitly. Even if they do not like the warm interior model, most team members would admit it is still the best explanation going for Enceladus's perplexing surface.

"Ideas are often wrong, so we really hit hard at them," says Larry Soderblom after dinner. "If they stand up under attack six or more times, some of us start to accept them."

On the other hand, Soderblom is starting to question some well-accepted ideas about how these moons formed. Supposedly they accreted slowly and relatively uniformly from the disk of dust and gas surrounding a young Saturn. But the moons have such unexpected densities. Being closer to Saturn, Mimas should have lost more of its rockier grains to the mother planet than Tethys, yet it is rockier than Tethys. Dione is likewise rockier than farther-out Rhea and may have been active longer. Evidently these moons are not all made from the same stuff.

"Say all the pieces that make up a moon are the size of a marble. Then even if there are lots of different colors of marbles, the moon would average out gray," says Soderblom. "But if instead the pieces are each 100 kilometers across, their colors wouldn't mix so anonymously. If just 30 pieces made up Tethys, it could have its own personality."

Thus it could have been chance that most



JAMES A. SUGAR

Trading insights *while the first data on Saturnian wind speeds and directions are plotted, Andrew Ingersoll and Reta Beebe begin the long, detailed process of putting numbers to observed phenomena. As mission chief scientist Edward C. Stone has put it, "Until you have numbers, you don't have a science."*

Spaceworn Dione, *mother of Aphrodite in mythology, reveals **(facing page)** fissures, craters, and, on the sunlit limb, evidence of coating from internal upheaval and escaping gases.*

Pondering a lunacy of moons

A NEW CLASS OF MOONS, larger than all but the largest asteroids but smaller than Jupiter's Galilean satellites, presents a set of puzzles to scientists **(above,** *from left) Laurence A. Soderblom, Richard J. Terrile, Torrence V. Johnson, and, standing, Eugene Shoemaker. If the moons had fit neatly with predictions, they should have been uniformly dead ice and dust balls, peas in a pod, except that their densities likely would have increased with distance from the planet.*

Instead, they proved to be significantly different from each other, some with evidence of internal activity, now or in the past, with densities changing randomly without regard to distance from the planet.

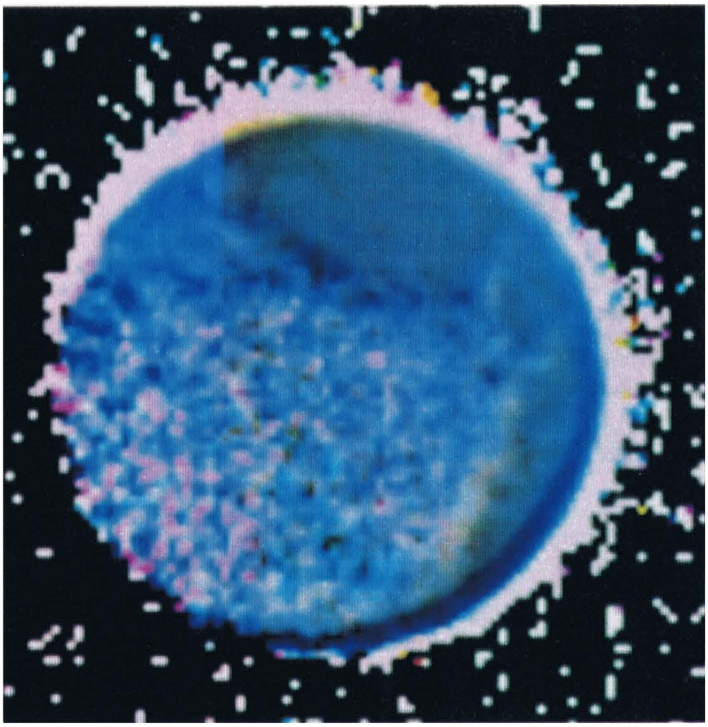
JAMES A. SUGAR

Tethys

Like an old tennis ball chewed by the family dog, Tethys **(left)** *shows a long, sinuous trench about three kilometers deep and the tooth marks of large craters. Perhaps the least dense of Saturn's icy moons, Tethys is 80 percent or more water ice.*

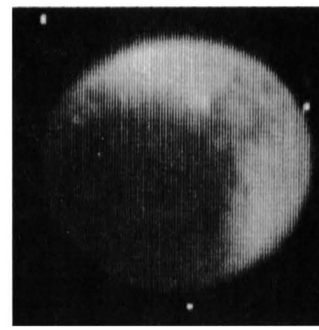
Besides the moons' relative distances from the planet, their densities may differ because of the various amounts and kinds of particles haphazardly accreted during their formation. The least dense may have rocky material scattered randomly throughout, while in the most dense the rock may have segregated and sunk toward their centers.

Those indicating geologic activity may have been heated during accretion or later by radioactive decay of rocky material.



Iapetus

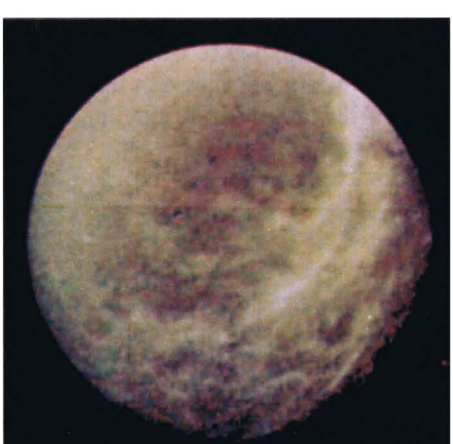
A yin and yang of a moon, Iapetus has one hemisphere five times brighter than the other, as seen in both enhanced false color **(left)** *and in direct imaging* **(below)**. *The cause is not known, but Voyager 2 will come in for a much closer look.*

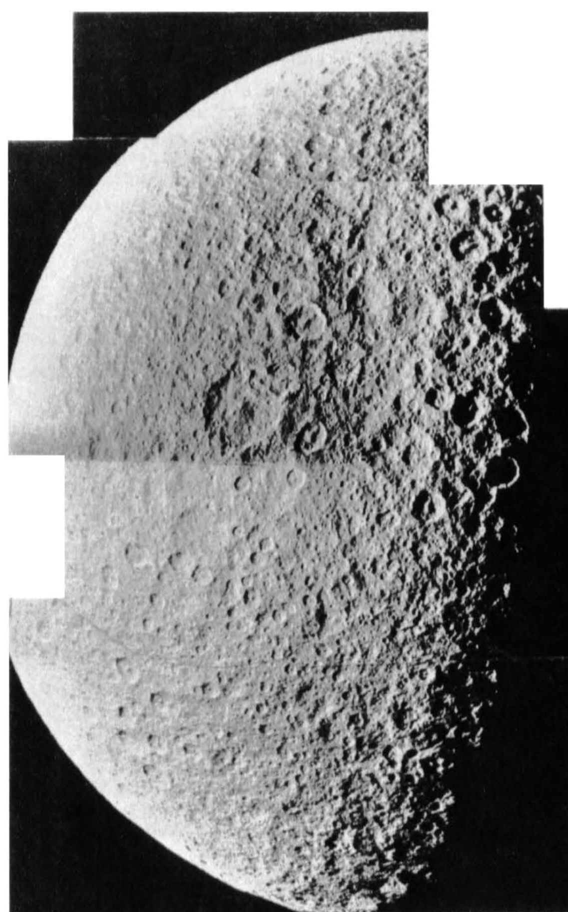


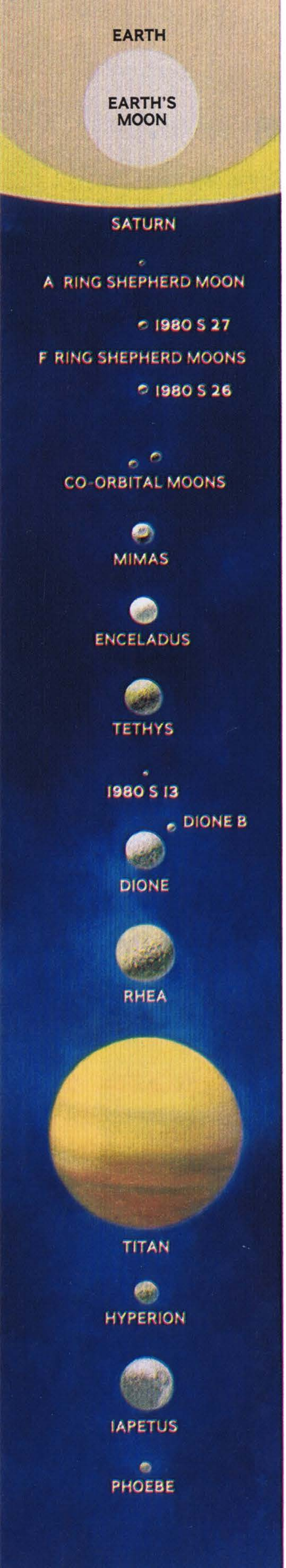
Rhea

Rhea's insides were stirred, probably very early in its history, for as seen in color at low resolution **(below)**, *white wisps indicate that water spewed out from the interior. A closer view of another region* **(right)** *shows intense cratering.*

Some craters on Saturnian moons may be the products of other craters. When a high-speed body strikes a small moon, some debris goes into orbit and eventually impacts at low speed on the same moon.







Saturn's moons

Earth and its moon are superimposed to scale on Saturn. Saturn's larger moons are also shown to scale.

DIA diameter in kilometers
DIS distance from Saturn's center in kilometers
DEN density; water = 1.0
* moons not to scale

A ring shepherd (1980 S 28).* DIA 30 km; DIS 137,700 km. Smallest of the satellites.

F ring shepherds (1980 S 27, S 26).* DIA 220 km, 200 km; DIS 139,400 km, 141,700 km. These hold the F ring in place.

Co-orbital moons (1980 S 1, S 3).* DIA 180 km, 120 km; DIS 151,450 km. May be halves of a single fractured satellite.

Mimas.* DIA 390 km; DIS 185,500 km; DEN 1.2 A nearly fractured moon scored by cracks.

Enceladus.* DIA 500 km; DIS 238,000 km; DEN 1.1 (?) The most reflective body in the solar system.

Tethys. DIA 1,050 km; DIS 294,700 km; DEN 1.0 Almost totally water ice with great cracks perhaps due to freezing expansion.

16th moon (1980 S 13).* Not yet confirmed.

Dione. DIA 1,120 km; DIS 377,400 km; DEN 1.4. Has wispy streaks, probably frost.

Dione B (1980 S 6).* DIA 50 km; DIS 377,400 km. Shares the orbit of Dione, probably similar to other icy moons.

Rhea. DIA 1,530 km; DIS 527,000 km; DEN 1.3 Surface variable, may have had several bombardment eras.

Titan. DIA 5,140 km; DIS 1,221,800 km; DEN 1.9 Has an atmosphere much denser than Earth's.

Hyperion.* DIA 290 km; DIS 1,479,300 km. Poorly seen by Voyager 1.

Iapetus. DIA 1,440 km; DIS 3,558,400 km; DEN 1.2 Extreme variation in reflectivity between hemispheres.

Phoebe.* DIA 50 km; DIS 12,945,000 km. A captured moon with a retrograde orbit.

PAINTING BY DAVIS MELTZER

of the chunks that made up Tethys were icy. And those going into Dione might have had more radioactive rocks than Rhea's, keeping Dione's interior hot longer.

Radioactive rocks help heat the interiors of terrestrial moons and planets. "We never thought these moons were big enough to generate the heat needed to provoke the eruptions apparent on Voyager's moonscapes," says Soderblom.

This is the outer solar system, however. Earth's geology may not apply to moons with compositions like comet nuclei. Toby Owen suggests the moons could be active chemically rather than geologically. One comet, known as Schwassmann-Wachmann 1, whose orbit keeps it between Jupiter and Saturn, periodically explodes for no known reason. Perhaps something sparks a pocket of unstable gas within. Similar blowouts of gas and dust—chemical volcanism—could be resurfacing the cometlike moons of Saturn, as well as supplying the E ring with particles, says Owen.

JANUARY 14, 1981. The Voyager imaging team is reconvening at JPL to write its first mission report. The scientists are still struggling to make sense of the rings. Many now concur that there may indeed be lots of little moons lurking in the rings, dominating their dynamics. After seeing that the two co-orbital moons may once have been one, and that Mimas has nearly been smacked to pieces, some team members are conceding that the rings could have had a catastrophic origin. Others are rethinking their ideas on accretion. How could moonlets grow as big as 1 to 15 kilometers within the Roche limit? Some suggest ring particles could still be accreting.

Some scientists feel they can now at least better describe, if not explain, what Voyager saw in Saturn's rings.

The rings not only are dynamic but also have remarkably different characters. For instance, the C ring and Cassini Division particles appear significantly darker than A and B ring particles. And data from the radio-science team show that particles in the A ring and Cassini Division are five times larger than those in the C ring.

To ring expert Jeff Cuzzi this implies that each ring may have a different history. The structure of the A ring is orderly. Many gaps in the A ring, he says, are clearly caused by satellite resonances. But there are also other highly regular patterns that look like the grooves in a record. These could actually be waves induced by resonance.

The B ring turns chaotic. Some ringlets are close together, some far apart. This is where most of the suspected moonlets lurk. The B ring is dense and opaque. Its many large pieces churn and grind against each other, generating clouds of fine ring dust.

This dust is what gets lifted up out of the ring to become the spokes. Jim Warwick, leader of Voyager's planetary radio astronomy team, believes that sunlight charges these minute particles. He also thinks that they then coat the larger ring particles. Warwick suspects that a thickly coated and thus highly charged moonlet travels through one region of the B ring. As it does, electricity leaps between the moonlet and countless smaller particles.

The result is a continuous static chorus of what sounds like lightning and might look like it too if the rings had an atmosphere to flash through.

The border between the B and C rings, says Cuzzi, is perplexing. There is no gap. But the C ring clearly contains much less material than the B ring. Its particles are probably much smaller. It is more transparent, has a different color, and shows orderly structure.

"Maybe the C ring is populated by fresher material," says Cuzzi. "Maybe A and B were the original rings and C was created more recently. Maybe micrometeorites sputter molecules off chunks in the B ring, and they land in the C ring and accrete into new particles."

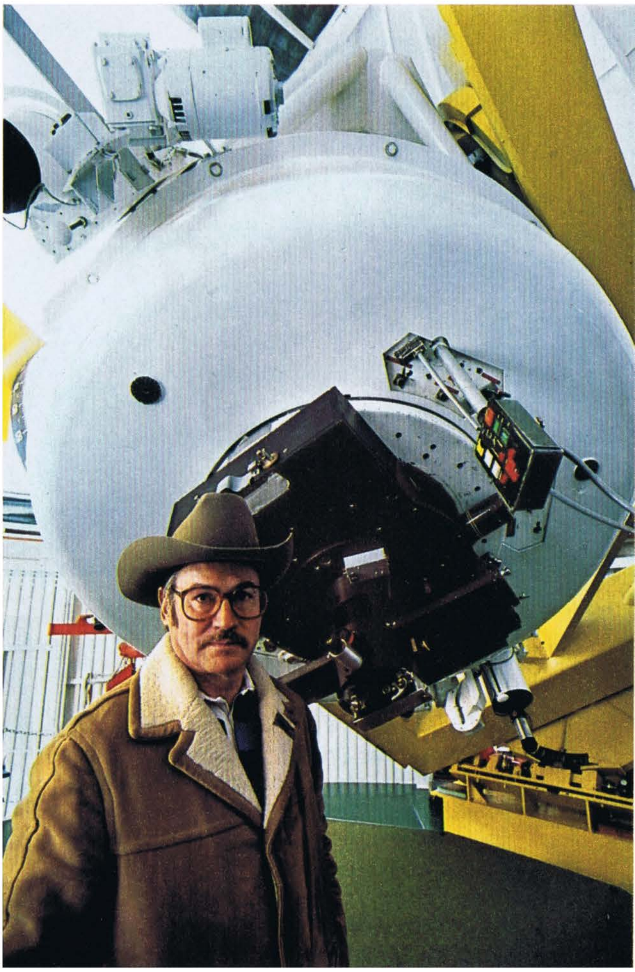
As for the F ring, Rich Terrile says, "It's still braided. We couldn't make those pictures go away. Most team members think the gravitational forces from the shepherding satellites send 'traveling pulses' along those strands as they speed by. Both those satellites' orbits are eccentric, so a pulse from one of them could be 16 times stronger on one side of the ring than on the other. No wonder it is kinked, clumped, split, and tied up in knots.

"We're going to be working on this ring for a long time," says Terrile.

FEBRUARY 11, 1981. The first science report is complete, and Brad Smith is looking at Saturn through a 61-inch telescope in the Santa Catalina Mountains outside Tucson. He hopes to confirm a sighting he made last year of a 16th Saturnian satellite.

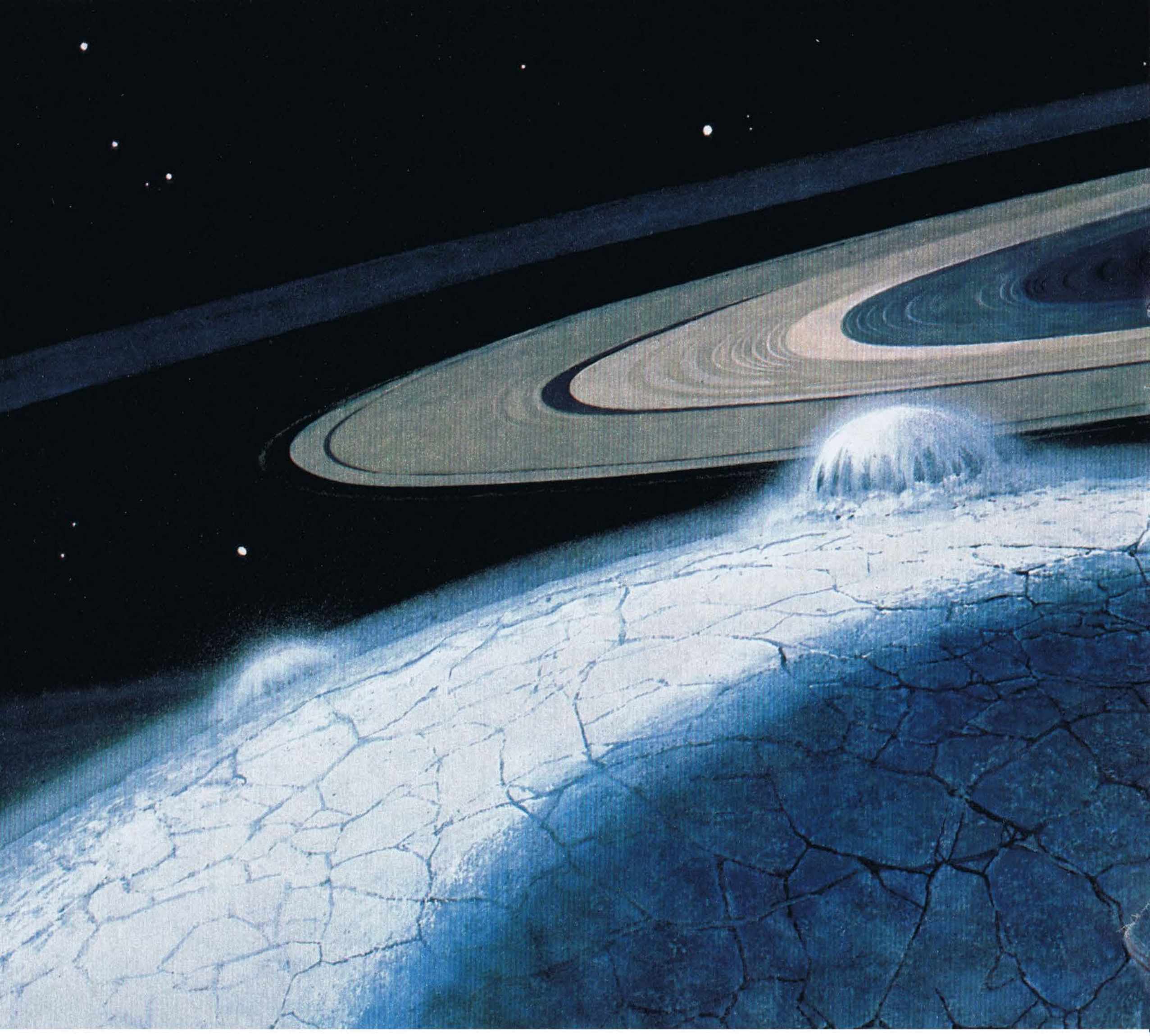
Through the lens appears the frosty haloed sphere that has sparked rapture in every observer since Galileo. It is hard not to gasp, hard to believe there is really something up there that looks like that.

"This is the way I've always seen Saturn," says Smith. "I've spent quite a bit of my life



KERBY SMITH

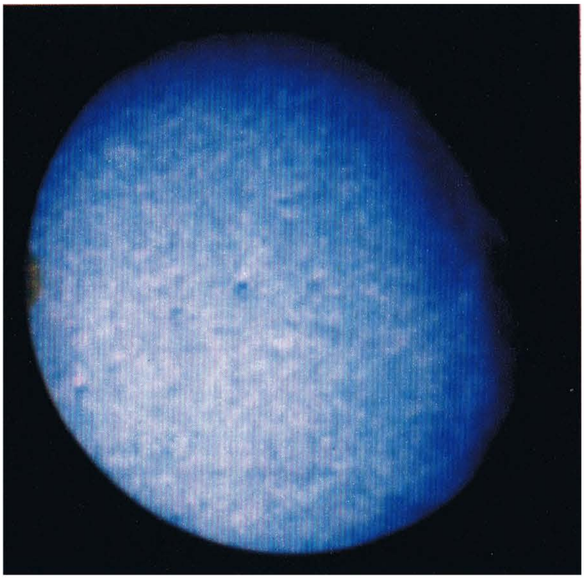
Riding herd *on Saturn with a 61-inch telescope, Voyager imaging-team leader Bradford A. Smith tries to confirm a 16th satellite. When it comes to the Saturn system, he says, "We're still a long way from a detailed understanding."*



Shining Enceladus

MIRROR OF THE SOLAR SYSTEM, Enceladus (**right**) *reflects nearly all the light that reaches it. It may be that the satellite is continually being recoated from its interior (illustrated* **above**). *One hypothesis is that tidal forces—resulting from Saturn's and Dione's gravity—heat its interior. This keeps the moon a giant drop of water with a thin ice crust that can fracture to emit ice crystals, which can escape to feed the very faint E ring.*

Other ideas are that meteorites puncture the crust with the same effect, or that chemical volcanism involving methane might be responsible. Voyager 2 will perhaps have some answers—and perhaps even more questions.



PAINTING BY LLOYD K. TOWNSEND

squinting through eyepieces, wondering what it is really like. Now the romanticist in me is sad.

"I'm probably the only one who feels this way, but Voyager has taken the mystique away. The wondering is over. I now know what it looks like. Now it's become clinical."

The scientist in Smith, however, is just going to work. "At Jupiter we saw puzzling things, but by this time we felt we were in the mop-up stage of understanding them. I don't believe we've made any real progress on the structure of the rings."

Smith is wary of the idea that invisible moonlets create most of the ringlets in the B ring. "Why wouldn't they be in the A and C rings as well?" He thinks Voyager 2 will reveal far more structure still when it flies much closer to the rings late this August. With luck, Voyager 2 will take close-ups of the braiding in the F ring. Its cameras have been reprogrammed to try to observe the spokes as they form and dissipate. The surface of Enceladus will be seen in much greater detail. Yet Smith is concerned.

"I worry," he says, "that in August we'll find out that the sequence of images we've designed for Voyager 2 may not be the best, that we should have done it differently, and that we'll have lost a chance that may not come again in our lifetimes." He goes on, almost until dawn.

"We're dealing with such complex phenomena—with things that are just *very* different. It takes time," he says. "Saturn is becoming an obsession." □