The Puzzle That Is Saturn

The Voyager observations have always been outrageous; that is half the fun

For sheer intellectual fun, there has never been anything quite like the Voyager encounters. Volcanoes on Io, ringlets around Saturn, *braided* rings—the observations are outrageous. The ghost of Till Eulenspiegel grins from the video monitors: "Figure this one out if you can!"

Take the problem of the satellites of Saturn, for example. "The Saturnian system is icier, whiter, brighter, and junkier" than Jupiter's, says Torrence V. Johnson of the Jet Propulsion Laboratory. In addition to the nine major satellites there are the spacegoing icebergs trapped in the gravitationally stable Trojan points of the satellite Tethys, 60° in front of and behind it in its orbit. There is another iceberg in the Trojan point ahead of Dione. There are "coorbital" satellites playing tag with each other in their common orbit just outside the rings, and there are two irregular "shepherd" satellites, one just to the inside and one to the outside of the pencil-thin F ring. There is a tiny "guardian" satellite just outside the bright A ring (the outermost ring that is visible from the earth) and there are the billions of icy fragments in the rings themselves. What happened?

Eugene Shoemaker of the California Institute of Technology, an expert on crater formation, has a dark horse theory. He takes it seriously enough, although he explains it with a broad grin and cautions that it is purely hypothetical. As Johnson agrees, "it's fun to kick around."

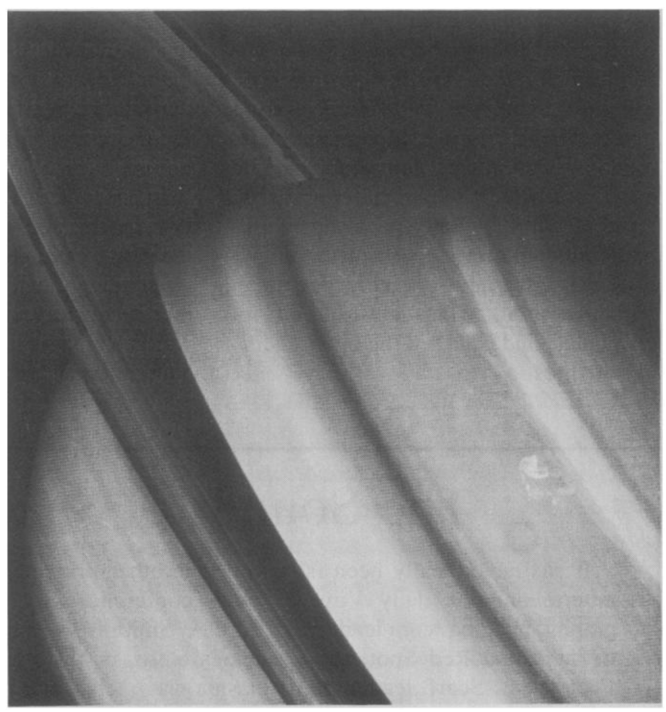
In the early years of the solar system, Shoemaker says, the outer solar system was swarming with cometary nuclei, dirty balls of snow and ice several kilometers in diameter. A conservative estimate puts their number at 100 billion. Shoemaker suspects that in aggregate they contained far more mass than the planets. In any case, close encounters with Jupiter, Saturn, Uranus, and Neptune tended to eject them from the solar system, and by about 3.5 billion years ago most had joined the Oort cloud (named after the Dutch astronomer Jan Oort, who first deduced its existence 30 years ago). The cloud is a vast, spherical halo of iceballs surrounding the sun some 0.1 light year out. Only when a passing star perturbs one of these objects back into the inner solar system do earthlings see it as a comet.

Before all these dirty snowballs were ejected, however, the outer planets—and their satellites—must have been subjected to a savage pummeling. The record is there on the crater-blasted faces of Tethys, Rhea, and Dione and in the huge crater that nearly shattered little Mimas.

All this is well known and widely accepted. But Shoemaker takes it one step further. He speculates that the satellites now in orbit around Saturn are not the original ones. The original system might have looked much more like the Galilean system of Jupiter, with several large bodies the size of Titan (roughly 5000 kilometers in diameter). Any such object would have been large enough to begin internal differentiation, he points out. Rocky material would sink toward the center of a larger globe of ice, heating the body by the release of gravitational energy. The cometary bombardment would heat the object still more, until the ice was nice and soft—and then wham! A larger comet, perhaps 200 kilometers across, would blast it to smithereens. Only later, as the bombardment was tapering off, would the fragments reaccrete into the smaller satellites seen today.

Titan, in this picture, was the only original satellite to survive, probably because it was quite far out. Saturn's gravity would have focused the cometary bombardment into the inner part of the system, Shoemaker explains. "It's a possibility that all the tiny satellites—even the ring particles—are simply fragments of the original system," he says.

Shoemaker notes that the Jovian satellites were also bombarded by comets—the scars are there on Ganymede and Callisto—but at a much lower rate. Jupiter is closer to the sun than Saturn, and the swarms there were less dense. Thus the Galilean satellites survived.



The ringed giant

From 13.9 million kilometers out, Voyager 2 returned this image of Saturn and its rings. In the midlatitudes is a white storm cloud about the size of North America.

Sometimes a trivial-sounding datum can have far-reaching implications. Stanford University's Von R. Eshleman, a member of the Voyager radio science team, describes one such case: an improved measurement of the density of the satellite Iapetus.

The Voyager scientists derive such densities from a satellite's size, as measured from the close-up photographs, and its mass, as determined by the radio

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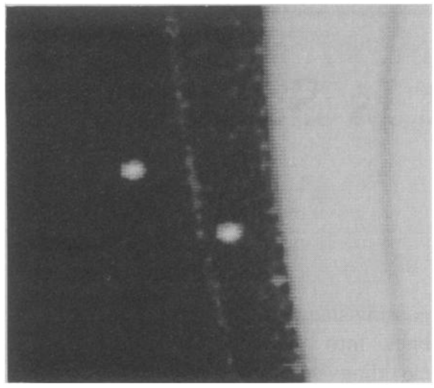
science team from perturbations of the spacecraft's trajectory. In particular, says Eshleman, during the close approach of Voyager 2 to Iapetus they derived a density of 1.1 ± 0.1 grams per cubic centimeter, down from the rough estimate of 1.3 made last November during the Voyager 1 flyby.

Satellite systems are thought to condense from a disk of gas and dust surrounding the central planet, explains Eshleman, just as the planets themselves condense from a much larger disk surrounding the sun. Presumably these disks would have the same composition as the sun: hydrogen, helium, and traces of elements such as carbon, nitrogen, oxygen, and silicon.

The composition of a satellite reflects the temperature of the surrounding gas and dust when it formed. The young Jupiter, for example, was quite hot; any satellites that formed close in should consist mostly of silicate rock, with a density of about 3 grams per cubic centimeter. And this is exactly what is found for Io and Europa, the innermost of the Galilean satellites. Farther out, the disk was cool enough for water ice to condense. Under those conditions the elements present in the solar nebula should have condensed to form water and rock in 60:40 ratio. A satellite made of this material would have an average density of some 1.3 grams per cubic centimeter—just about what is observed for Ganymede and Callisto, the outer Galilean satellites.



F ring with escorts

The F ring, the shepherd satellites, and the outer edges of the A ring are seen here, just a few hours before the slightly faster-moving inner shepherd overtook the outer shepherd. They seem to cause no kinking or braiding in the F ring.

Saturn also started out warm, says Eshleman, though not as warm as Jupiter. Thus all of its satellites are icy, and most have densities in the neighborhood of 1.3 grams per cubic centimeter. Iapetus, however, drifts in a lonely orbit more than 3.5 million kilometers from the planet, nearly three times as far as Hyperion or Titan, the next satellites inward. According to the calculations of Australian theorist Andrew J. R. Prentice, says Eshleman, these far-distant reaches of the nebula would have been cold enough to freeze even methane. In that case, material of solar composition would have yielded a mix of water, rock, and methane in a 55:35:10 ratio, with a density of about 1.1 grams per cubic centimeter—exactly what has now been determined for Iapetus.

Thus, assuming that this argument about the meaning of the satellite densities is correct, the Voyager 2 measurement has put Iapetus into a class by itself as the only satellite known to contain a significant fraction of methane. And it may be no coincidence that Iapetus is also the only satellite known to have a division between light and dark hemispheres. From a first look at the Voyager 2 close-ups of Iapetus it seems that the dark material has welled up from within, pooling in the bottoms of craters. "In the top 1 inch alone there are 15 billion tons of carbon in that methane," Eshleman points out. "And there are plenty of ways to make black stuff out of carbon." Perhaps the dark material is simply carbon black. Or perhaps it is some hydrocarbon created through the action of sunlight on methane. "Maybe it's black as pitch because it *is* pitch," he says.

Voyager 2 did not get a very good look at orange, smog-shrouded Titan, by far the largest satellite of Saturn, and the only satellite in the solar system known to have an atmosphere. From a distance of 665,960 kilometers the photopolarimeter did verify that the smog particles are tiny things, 0.1 micrometer or less. (This was a first. Voyager 1's instrument had failed at the Jupiter encounter in 1979.) And the cameras did show that the dark, mysterious polar hood had somehow become an equally mysterious polar headband. For the most part, however, the Titan specialists on the Voyager team were still pondering the questions raised by Voyager 1, which passed just 6490 kilometers from the satellite last November.

Some things are reasonably well understood by now. For example, Voyager 1 found an atmosphere of 85 percent nitrogen, presumably formed by the photolysis of ammonia in the ultraviolet-drenched upper atmosphere, and 12 percent argon. Most of the rest is methane. And this latter is very important, notes Rudolf A. Hanel of Goddard Space Flight Center, principal investigator on Voyager's infrared experiment. The hydrocarbons detected in Titan's atmosphere—compounds such as ethane, acetylene, ethylene, and hydrogen cyanide—are what one would expect to see in a mix of methane and nitrogen that has been exposed to sunlight. Charged particle interactions must also play a role, adds Darrell F. Stobel of the Naval Research Laboratory. Titan spends a good part of its time within Saturn's radiation belts, where energetic particles can buf-

The Sounds of Space

It has never really been fair: while the other principal investigators are entertaining the daily Voyager press conferences with data tables and graphs, imaging team leader Bradford A. Smith is waiting with color slides of the Great Red Spot, the volcanoes of Io, or the rings of Saturn. But Fredrick L. Scarf, leader of the plasma wave team, has at last gone Smith one better.

Scarf's experiment measures oscillations in the electrically charged plasma surrounding the spacecraft, oscillations whose frequencies happen to fall in the acoustic range. By playing the signal back through a conventional loudspeaker, Scarf creates "the sounds of space," an eerie symphony of hisses, pops, and whistles. Voyager's transit of the bow shock, where the solar wind first encounters the magnetic field of the planet and is forced to flow around, erupts from the speakers as a hoarse roar like the breaking of waves on a beach.

For the Voyager 2 encounter with Saturn, Scarf and his colleagues outdid themselves: they played their data, which were divided into 16 frequency channels, through a 16-channel music synthesizer. The fragment of music that results is fitting accompaniment to Voyager's journey past Saturn. Slowly, dreamily, the midlevel brasses surge and ebb against a deep roll of basses and a high, floating treble. The music lasts for only a minute. But it haunts the mind.—M.M.W.

fet the upper atmosphere with ten times as much energy as solar ultraviolet does.

"The smog is the logical continuation of the photochemistry and magnetospheric chemistry," explains James B. Pollack of Ames Research Center. "The process keeps going until you get compounds of high enough molecular weight. Then they condense into smog particles." The smog layers are 200 kilometers thick on Titan; it takes about a year for a particle to drift down to the surface. Once there, however, it is in deep freeze. The surface of Titan is about 95 K at the equator and a chilly 93 K at the poles. Over its 4.6-billion-year lifetime, Titan must have accumulated hundreds of meters of hydrocarbon deposits (*Science News* reporter Jonathan Eberhart dubbed the stuff "OPEC-ite").

But there are problems with this elegant picture. Why is the smog orange? All the hydrocarbons so far found on Titan are colorless. Laboratory experiments by Carl Sagan and B. N. Khrae of Cornell University indicate that very complex, reddish compounds might form after months of irradiation. But in such laboratory experiments the chemistry is affected to some extent by the walls of the reaction chamber, and Sagan admits that it is not clear how well the results extrapolate to the open air of Titan.

Another problem is that Titanian photochemistry is a one-way street. It destroys the methane and hands the carbon over to the smog, which carries it down and locks it up in the hydrocarbon deposits. So how is methane replenished in the atmosphere? Presumably there is some methane ice mixed in with the water ice that forms the bulk of Titan, and presumably that methane slowly sublimates to replace what is raining out. But wouldn't the hydrocarbon snow have long since buried the surface ices?

Maybe. But it is important to remember that Titan's surface environment is close to the triple point of methane. "There are probably layers of methane clouds in the troposphere," says Hanel, "and we cannot rule out bodies of liquid methane on the surface." The vision this inspires is almost irresistible: methane oceans, methane rains, methane rivers thundering through canyons in the OPEC-ite mountains—or perhaps even a Titan-wide ocean, into which the eternal hydrocarbon snow vanishes softly, silently, without a trace.

"What we really need," muses Sagan, "is a Titan Orbiting Imaging Radar."

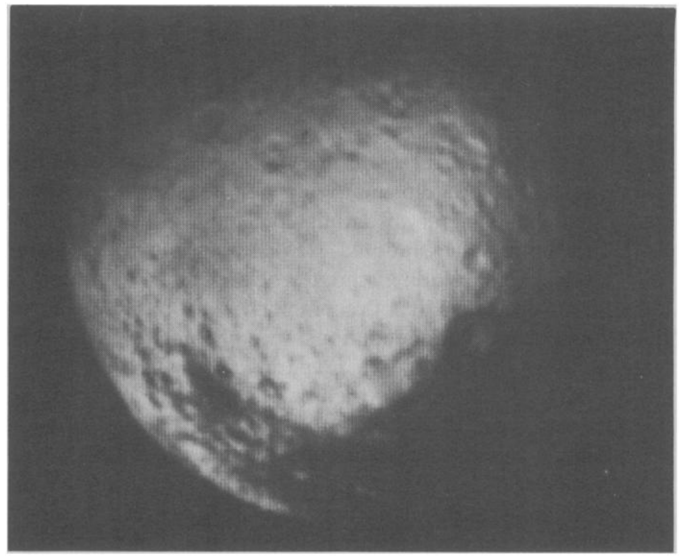
The rings of Saturn can only be described as maddening. Consider the F ring. During Voyager 1's approach to Saturn it was visible in the images as a pencil-thin line just outside the broad, bright rings known from the earth. Then Voyager 1 took close-ups: in violation of all commonsense celestial mechanics, the F ring was kinked, clumpy, and appeared to have three braided strands.

In the 9 months between Voyager 1 and Voyager 2 theorists expended considerable effort trying to understand the F ring. Electromagnetic effects on very fine dust particles, perhaps? Wavelike resonances with the little shepherd satellites just inside and outside the ring? Nothing was proved, but several ideas looked promising.

Then came Voyager 2. No braids in the F ring. No kinks. Five strands. And, as if to mock the theorists further, there was the "Encke doodle," a faint thin strand wandering through the Encke division in the A ring, with a well-developed set of kinks and not a shepherd moon in sight.

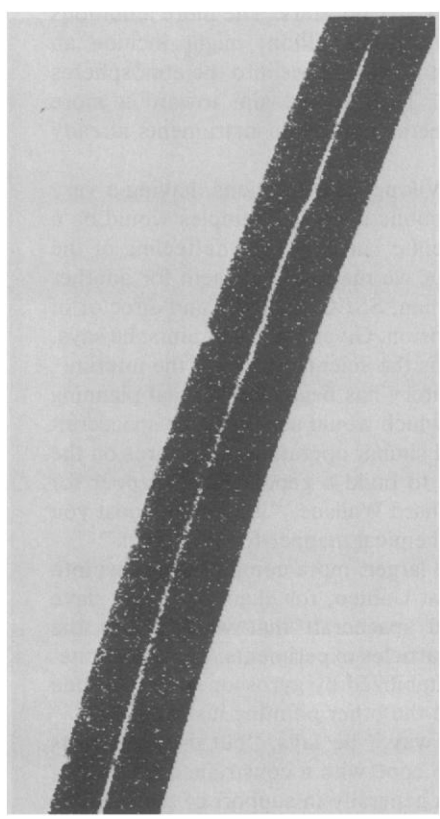
Whatever the vagaries of the braids, it is widely accepted that the F ring as a whole is confined to its narrow course by the shepherd satellites, which exert gravitational perturbations that tend to focus the ring particles between them. A similar mechanism had been thought to explain the ringlet structure in the bright rings, which makes the Voyager images of the rings look like close-ups of a phonograph record. The larger ring particles, "embedded moonlets," would herd the smaller particles into ringlets. But after 3 days of peering at Voyager 2's high-resolution imagery, the theorists had pretty much given up: there were no moonlets.

There were compensations, however, in the form of new mysteries. The Voyager imaging team, under Bradford A. Smith of the University of Arizona, prepared enhanced false-color images to bring out subtle differences between various parts of the rings. Presumably these differences would reflect variations in composition, surface properties, or size of the ring particles. What they saw was as disconcerting as it was lovely. The C ring (the innermost ring visible from the earth) for the most part showed up blue and white. But nestled among its close-packed strands were thin, isolated, sharply defined strands of gold. Somehow, the agency that made the ringlets



Iapetus

Voyager 2 looked down on the northern hemisphere of Iapetus from a distance of 1.1 million kilometers. In this view the satellite is lit from below. The bottom edge is not in shadow; it is just very, very dark.



The Encke doodle

Voyager 2 discovered a new "kinky" ringlet in the Encke Gap in Saturn's A ring. The kinks seem more closely spaced than those in the F ring.

had managed to sort the ring material first.

The golden threads of the C ring are the same color as the inner region of the B ring, thousands of kilometers farther out. Perhaps there is some connection. But the B ring itself is not uniform, as shown in another of the imaging team's productions. "At first we thought this was one of those abominations that sometimes comes out of the processing lab when the wrong button gets pressed," says Smith. "We sat on it for 3 days. Then we decided it was real." From its golden orange inner edge, the B ring undergoes a rainbow metamorphosis into turquoise at its outer edge. The images are saying something important. But what?

More information on the ring particles—100 billion bits of information—comes from Stanford University's G. Len Tyler and his radio science team. Last November, as Voyager 1 passed behind Saturn, it briefly beamed its radio signal back to the earth through the rings. Tyler and his crew are still analyzing those data.

"We find that nature is not only making ringlets, it's distributing particle sizes differently within the ringlets," he says. "For example, we often find ringlets where the fine particles are denser on the inner and outer edges than they are in the middle." The rings as a whole seem to consist of a tenuous background sheet of material, with empty gaps and denser ridges superimposed on it. A typical ridge has a very sharp edge, he adds. There is no hint in the data that one is coming up.

By comparing the attenuation of the microwave signal at two wavelengths, 3.6 and 13 centimeters, the radio science team has also been able to estimate the size distribution of ring particles. There are about 120 to 200 particles per square kilometer in the size range 9 to 11 meters and virtually none larger than that, says Tyler. The numbers—and uncertainties—rise rapidly with decreasing size. In the 3- to 5-meter range, for example, there are between 1700 and 6000 particles per square kilometer. There may be millions that are smaller than that, or there may be none; the radio data are consistent with either interpretation.

During the flight over the rings on 25 August, the Voyager 2 photopolarimeter obtained what are probably the most spectacular results of the mission. By monitoring the light of the star Delta Scorpii as it twinkled up through the ringlets, team leader Arthur L. Lane and his colleagues have mapped over 70,000 kilometers of ring material to a resolu-

To the Planets, Cheaply

Even as Voyager 2 was drawing close to Saturn, planetary scientists back on Earth were closing ranks behind a new approach for keeping the American planetary program alive and healthy in the face of continued fiscal stringency. The National Aeronautics and Space Administration's Solar System Exploration Committee (SSEC) met last month in La Jolla, California, to draw up a list of recommendations based on this approach, and on 24 August the recommendations were presented to NASA administrator James M. Beggs for his use in preparing the agency's budget proposal for fiscal year 1983. The idea, which has been gaining ground in the community for the last year or so, is simply that most future missions will have to be simpler and cheaper than they have been in the past. Unlike Voyager or the Viking Mars landers, they will not advance the state of the art. They will use standard spacecraft designs and off-the-shelf instrumentation as much as possible. They will also tend to carry fewer instruments, and will focus very sharply on specific scientific questions.

"Over the last decade our missions have been getting bigger, more complex, and more expensive—and we've been doing them less and less often," says Andrew J. Stofan, acting head of NASA's Office of Space Science. "We can't keep on this way." Budget cuts earlier this year forced NASA to cancel its plans to join with the Europeans in the International Solar Polar Mission, and its chances of sending a spacecraft to Halley's comet in 1986 look bleak (*Science*, 17 April, p. 316). Stofan warns that another major cut would mean the cancellation of the Galileo orbiter/probe mission to Jupiter.

The SSEC identified three classes of unmanned planetary missions. Those in the limited-scope, Pioneer class would cost perhaps $100 million to $150 million each in 1981 dollars. Examples would be simple orbiters to study the upper atmospheres of Mars and Venus, or an orbiter to map the distribution and seasonal migration of water on Mars. The more ambitious Mariner-class missions, costing about $500 million, might include an asteroid rendezvous or a Saturn flyby to drop probes into the atmospheres of the planet and its satellite Titan. They would aim toward a more comprehensive exploration, using cameras and other instruments already developed for Voyager and Galileo.

Finally, there are the billion-dollar Viking-class missions, having a very broad scientific scope and maximum public appeal. Examples would be a Mars sample return or a Galilean satellite lander. "It's the feeling of the SSEC that we need such missions, but we may not get them for another decade or more," says Daniel H. Herman, SSEC chairman and director of NASA's Solar System Exploration Division. Given the constraints, he says, the first two types will be what sustains the science teams in the interim.

Recently, the Jet Propulsion Laboratory has begun conceptual planning for a set of Mariner Mark 2 missions, which would use the same spacecraft bus, the same onboard computers, and similar operating procedures on the ground. "If it costs you $300 million to build a geochemical mapper for Mars," says JPL mission designer Richard Wallace, "it may only cost you $100 million to build an identical geochemical mapper for the moon."

Another approach is to break up the larger, more complex missions into several pieces. Herman points out that Galileo, for example, might have been separated into a spin-stabilized spacecraft that would carry the atmospheric probe and the fields and particles experiments, and a separately launched Voyager-like spacecraft, stabilized by gyroscopes and attitude jets, that would carry the cameras and the other pointing instruments.

"The total cost would be more that way," he says, "but the peak costs would be less, so it would be easier to cope with a constrained budget."

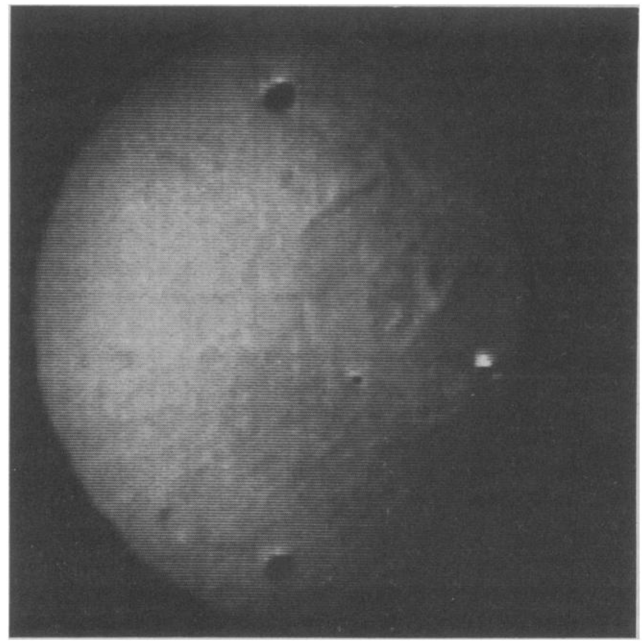
The planetary science community is generally in support of the science-focused approach, says Stofan. Even in the best of times it would be a good, commonsense way to do things. But right now, it's a matter of survival. As Wallace points out, "We're scared to death the whole planetary science program is going to go down the tubes."—M. MITCHELL WALDROP tion of a city block. Where the imaging results show thousands of ringlets, the photopolarimeter results show hundreds of thousands—ringlets within ringlets within ringlets. In the first, quick look, the data show the bright central strip of the F ring resolved into no fewer than ten components—the thickest of which is itself split into two dense strands, each only 200 meters across. The A ring gives way to the Encke division in the space of less than 1 kilometer. The A ring's outer edge is equally sharp, and less than 150 meters thick. After 3 years of frustration, with a dead instrument on Voyager 1 and a radiation-damaged, extensively reprogrammed instrument aboard Voyager 2, Lane is a happy man indeed.

The famous dark spokes on the B ring remain as perplexing as ever. Voyager 2 showed that their edges are sharp to a resolution of 60 kilometers. The spacecraft also made a time-lapse movie (which has been dubbed the Saturn 500) following a group of spokes around the ring. (The ring particles are in orbit around Saturn and carry the spokes along with them.) The movie shows that as the older spokes fade, a fresh spoke forms, leaping radially across 20,000 kilometers of ring surface within about 12 minutes.

"Our impression is that the spokes are somehow imprinted on the rings by some action of Saturn's magnetic field," says Smith. "But the fact that they deposit so quickly surprises me."

Imaging team member Richard Terrile, of the Jet Propulsion Laboratory, says that the spokes are probably related to small particles in the ring. Perhaps dusty material on the surface of the ring particles is ionized by sunlight and then elevated above the ring plane by the magnetic field. "It doesn't have to be elevated very far to change the surface reflectance drastically," he points out. It is also tempting to associate the spokes with the electrical discharges detected by both Voyager 1 and Voyager 2, he says. The periodicity of the discharges matches the orbital period of the B ring material, where the spokes are strongest. But the association has not been proved.

For those who remember Voyager's psychedelic imagery of Jupiter, the butterscotch expanses of Saturn have to be something of a disappointment. It has nothing to do with high altitude hazes, as was once thought. Voyager 2, which carries a somewhat better camera than its predecessor, showed dark bands on Saturn that stayed crisp and clear all the way to the limb of the planet, with no sign of haze. Only with the blue and ultraviolet filters did the images show any scattered light near the limb, and at least some of that was due to Rayleigh scattering from the atmosphere itself. (Rayleigh scattering of sunlight by air molecules is what makes the earth's sky blue.) No, the planet is just bland.



Tethys

On Tethys, only 1050 kilometers in diameter, Voyager 2 found a crater 400 kilometers across, evidence of intense bombardment billions of years ago.

"Saturn is colder than Jupiter, and different temperatures imply different chemistries," says Andrew Ingersoll of the California Institute of Technology. "You have to remember that the atmosphere is mostly hydrogen and helium. An order of magnitude down from those in abundance you get water, ammonia, and ammonium hydroxide, the things that make the clouds. And only another order of magnitude down from them do you get the colors—whatever they are." Ingersoll also points out that the regions of active convection, where Jupiter's most spectacular weather occurs, are for some reason less abundant on Saturn.

Nonetheless, the atmospheric specialists were delighted with the Voyager 2 results. The better imagery of the cloud features is already paying off in a better map of Saturn's fierce winds, as well as a clearer view of the turbulence and vorticity in the atmosphere. As it happens, these matters are not unrelated.

"There's no solid surface on Jupiter or Saturn," says Ingersoll, "so once a jet stream gets started it will keep going for a long time. But there's also a maximum speed a wind can have before the shear forces break it up into waves and eddies. On Jupiter, the jet streams exceed that speed, and what we found when we mapped the flow was that the winds weren't driving the eddies, the eddies were driving the winds."

The Jovian jet streams run east and west like alternating conveyor belts, and the eddies roll between them, Ingersoll explains. The eddies do not just move passively, like ball bearings. They rotate faster than the winds, actively pumping momentum into them. The eddies themselves get their energy from convective upwelling, deflected into circular motion by Jupiter's 10-hour rotation and correspondingly strong Coriolis forces. The convection, in turn, is driven by the heat of the interior (4.6 billion years after it formed, Jupiter is still cooling off. It radiates twice as much heat from the interior as it receives from the sun. On Saturn the fraction is even larger.)

From Voyager 2's improved imagery it seems that the same mechanism is at work on Saturn. "We see enormous amounts of structure in the high latitudes," says Smith. "Lots of convection, strange, parallel meandering jets—it may even be more complex than Jupiter." Garry E. Hunt of University College, London, pointed out V-shaped trains of eddies, peeling off from a stationary convective cell like eddies behind an island in a stream. "We're much further along than we were last time," he said.

On 25 August Voyager 2 rounded Saturn and set course for Uranus, 4 years and a billion miles away. The first Voyager era is over, the spacecraft's original mission to explore Jupiter and Saturn is accomplished. Two years ago, writing in *Science* about the first Voyager encounter with Jupiter, the members of the imaging team said, "Our sense of novelty would not have been greater had we explored a different solar system." Today that statement sounds more fitting than ever. Voyager has given us a special kind of joy.—M. MITCHELL WALDROP