Voyager 1 at Saturn

The encounter was a riotous outpouring of data and discovery; in the afterglow researchers are sorting out what it all means

On 1 September 1979, 14 months ahead of Voyager 1, Pioneer 11 became the first spacecraft to reach the planet Saturn. It was a triumph. But when the Voyager researchers saw the data and images Pioneer was returning, some of them felt a little nervous.

The famous rings, seen for the first time by transmitted sunlight, were lovely. But the planet itself, orbiting a billion miles from the sun, showed up as a cold, pale, washed-out globe, its latitudinal banding barely visible. Titan, quite possibly the largest satellite in the solar system and the only one known to have an atmosphere, resembled a featureless orange berry. Even Saturn's magnetosphere was mild-mannered, with earth-like intensity and near perfect alignment with the planet's rotation axis.

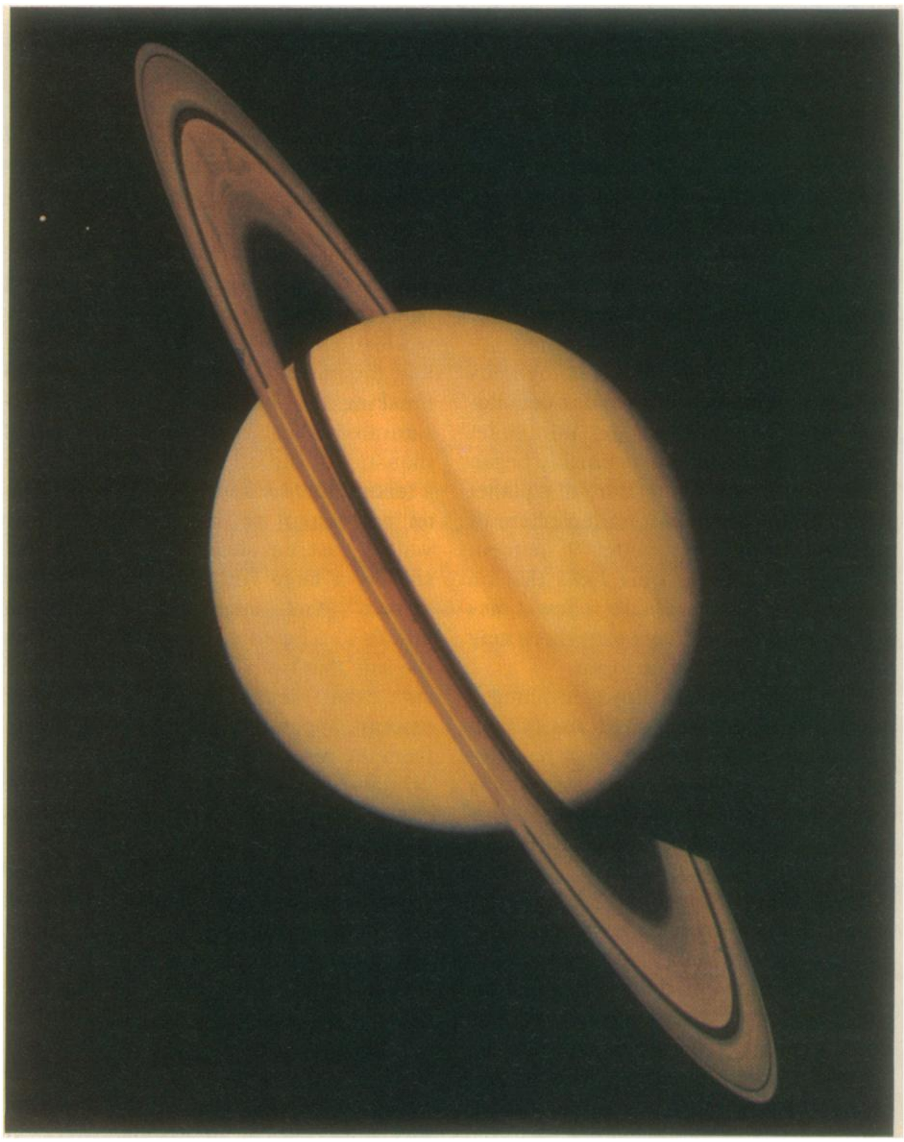
"We were scared," recalls University of Arizona astronomer Bradford A. Smith, leader of the Voyager imaging team. After the psychedelic cloud patterns, varicolored satellites, and fiendish radiation belts that had greeted Voyagers 1 and 2 earlier that year at Jupiter, the coming Voyager encounter with Saturn promised to be a pretty bland affair.

It wasn't.

In August, still more than 100 million kilometers out from the planet, Voyager 1 began continuous coverage of Saturn with a narrow-angle camera having some 50 times the resolution of Pioneer 11's imaging photopolarimeter. The scientists waiting at mission control at Jet Propulsion Laboratory (JPL), in Pasadena, California, soon began to see concentric substructure in the rings, bright ribbons and dark bands that gave the ring system the appearance of a phonograph record. By early November, as Voyager pulled within 10 million kilometers of Saturn, the scientists could count nearly 100 such features. But by then their attention had been captured by an even more baffling phenomenon: the "spokes," the radial, fingerlike darkenings that sweep randomly across thousands of kilometers of ring surface, as if someone were throwing out gargantuan handfuls of soot.

Meanwhile, in the weeks leading up to closest approach on 12 November, Voyager continued to monitor the motions of Saturn's atmosphere. In close-up, the planet turned out to show much of the same turbulent complexity seen on Jupiter. It looks less dramatic from a distance only because Saturn is colder and its clouds lie deeper, veiled by an overlying haze like Los Angeles seen from the air on a smoggy day.

Drawing closer still, Voyager was witness to a fascinating dance of satellites and rings. Just outside the rings visible from the earth, two tiny "sheepdog" satellites flanked the pencil-thin F ring, which had been one of Pioneer's principal discoveries. Closer in, virtually skimming the outer edge of the visible rings, was an even tinier sheepdog that seemed to be guarding against any material escaping outward. And a short distance outside the F ring were the two "co-orbital" satellites. Their orbits lie just far enough apart, some 50 kilometers, for the inner one to slowly catch up with the outer, but not far enough apart, given their roughly 150-kilometer diameters,



Saturn: A view from 18 million kilometers

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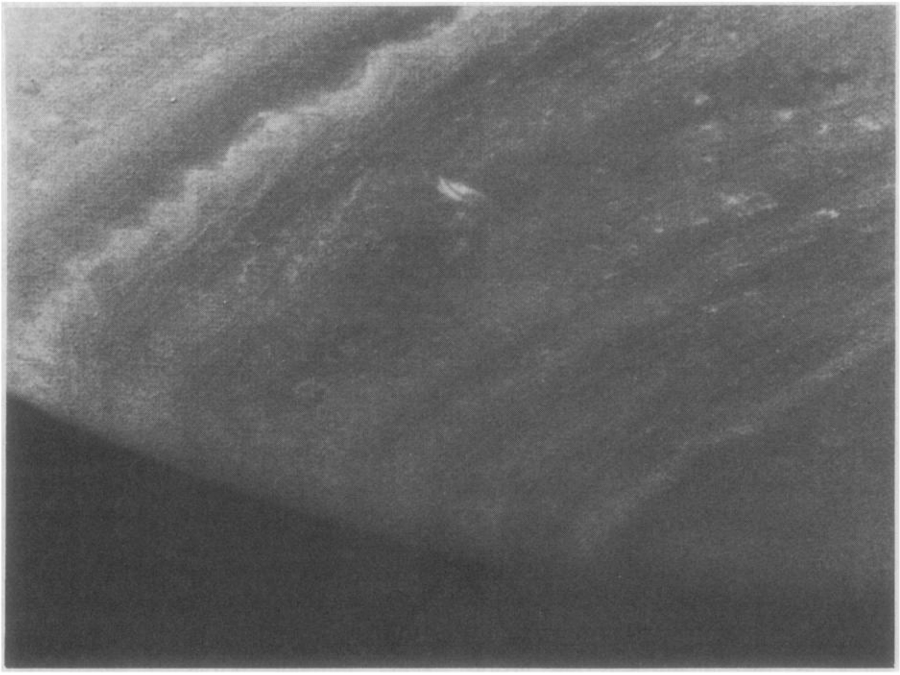


Veiled turbulence

Contrast enhancement of the Voyager images reveals the complexity of Saturn's smog-shrouded atmosphere.

for them to pass without colliding—at least, not without some totally non-intuitive gravitational interactions.

On the evening of 11 November, just as Voyager began its final sweep toward Saturn, it passed some 4000 kilometers from the surface of Titan, one of the prime objectives of the mission. The hoped-for break in the clouds never materialized; even in close-up the 5000-kilometer satellite was shrouded in impenetrable orange smog. But photographs are not everything. With radio occultation data plus infrared and ultraviolet spectra, mission scientists quickly began to build up a tentative picture of a planet swathed in a nearly pure atmosphere of nitrogen, containing about 1 percent methane. And there were hints that on the surface, at a pressure a few times greater than that of the earth, there may be an ocean of liquid nitrogen.

Picking up speed, Voyager plunged quickly through a tenuous torus of neutral atomic hydrogen, which it had discovered by Lyman alpha emissions only a few days before, filling the space between the orbits of Titan and Rhea, the next satellite inward.

Then, on 12 November, as it hurtled along the hyperbolic trajectory that would bring it within 124,000 kilometers of the Saturnian cloud tops, Voyager began a period of discovery to rival anything it had experienced at Jupiter.

There were the rings themselves, vastly more detailed in close-up, showing hundreds, perhaps even a thousand ringlets—a few of which somehow managed to be slightly elliptical and off-center to the rest.

There was the F ring, revealed in Voyager's narrow-angle camera to be kinked and triply stranded—and, perhaps, in defiance of all commonsense celestial mechanics, braided.

Then there were the smaller satellites. They suddenly grew from points of light bearing names out of mythology into icy worlds . . . Mimas, with a crater so huge that the impact must have come near to breaking the satellite apart . . . crater-saturated Rhea, mapped in finer detail than any of the others . . . Tethys, with a feature that looks like an immense crater but cannot be, because the "crater walls" cast no shadow . . . Dione, ensnaring a large ringed basin in "wispy terrain" that might be a mass of cracks . . . Iapetus, six times brighter on the side that trails in its orbit than on the side that leads . . . and Enceladus, smooth, apparently uncratered, different from the rest, locked with Dione in a 2:1 orbital resonance that may cause the same kind of tidal heating that powers the volcanoes of Jupiter's Io.

And then finally, as Voyager receded from the planet on its long journey out of the solar system, there were the images of the crescent Saturn encircled by translucent, spun-glass rings, its nightside pearly with ringlight.

"We've learned more about Saturn in the last week than in the entire span of recorded history," exulted Smith on the day after closest approach. "We can hardly concentrate on one of these pictures before we're distracted by another."

True enough. Voyager's dramatic imagery inevitably dominated both the early science and virtually all of the press coverage. But the imaging laboratory was not the only place where the champagne was flowing that week. "There are more than 100 scientists involved with 11 investigations on Voyager," emphasized head mission scientist Edward C. Stone of the California Institute of Technology.

In addition to two cameras, Voyager 1 and its twin Voyager 2, now headed for an August 1981 rendezvous with Saturn, each carry ultraviolet and infrared spectrometers. The latter instrument can also measure temperatures. A photopolarimeter is on board for aerosol studies, although Voyager 1's instrument failed at Jupiter and was not operating at Saturn.

Three charged-particle instruments monitor planetary radiation belts, cosmic rays, and the solar wind. Two magnetometers are mounted on a 13-meter boom, and the two 10-meter whip antennas listen for plasma waves, planetary radio emissions, and solar-stellar radio bursts.

Finally, even Voyager's radio link with the earth is an instrument, measuring reflectivity, absorption, and scattering in intervening material as the spacecraft passes behind a planet, satellite, or ring system.

Launched in 1977, the twin Voyager spacecraft are the result of planning that reaches back more than a decade. The Grand Tour, as the idea was originally called, would have taken advantage of a rare celestial alignment in the 1970's and 1980's that would have allowed a single spacecraft to visit all the outer planets, including Pluto. The less expensive Voyager program, substituted in 1972, focused only on Jupiter and Saturn. Nonetheless, the spirit of the Grand Tour lives on in current plans to direct Voyager 2 around Saturn in a trajectory that will take it on to Uranus in 1986 and possibly to Neptune in 1989.

During any planetary encounter the data comes in an avalanche, and so it was with the Saturn flyby. Sorting it all out will take months or even years, as the Voyager scientists try to build a detailed comparative planetology for the denizens of the outer solar system.

In the broadest terms, the structure and evolution of these planets have been understood for some time now. Large enough to retain all their original material from the solar nebula, they consist almost entirely of hydrogen and helium in the same ratio as in the sun. Their outer

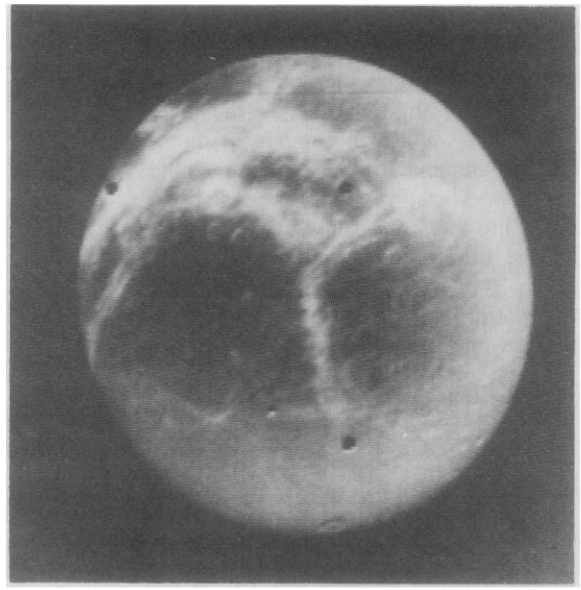
1000 kilometers or so is gaseous, banded with clouds formed from compounds of hydrogen with far less adundant elements such as carbon, nitrogen, and oxygen. Farther down, with increasing heat and pressure, the hydrogen becomes liquid. Farther still, at a pressure of roughly 1 million to 3 million atmospheres, the hydrogen becomes not only liquid but metallic. Presumably this conducting core is analogous to the molten iron core of the earth; in either case, convection in the core sets up a planetary magnetic field. Finally, in the center of the planet there may be a rocky core a few times the size of the earth and 15 to 20 times the earth's mass.

One man who has thought a great deal about the evolution of the gas giants is James B. Pollack of NASA's Ames Research Center in Mountain View, California. In 1974, following ideas first put forward by Peter Bodenheimer of the University of California, Santa Cruz, Pollack and his Ames colleague Ray Reynolds traced the development of Jupiter, using a computer model first invented to describe the evolution of stars. Then in 1977, Pollack, Allan Grossman of Iowa State University, and Harold Graboske of Lawrence Livermore Laboratory extended the model to include Saturn.

"We started out from the observation that both Jupiter and Saturn radiate about twice as much heat to space as they receive from the sun," recalls Pollack. "We thought that perhaps the excess might be due to the release of gravitational energy as these gas balls cool and contract."

In the computer model, the planet starts out as a gaseous sphere several hundred times its ultimate size. When its interior grows hot enough molecular hydrogen dissociates into atomic hydrogen, disrupting the hydrostatic equilibrium and triggering a catastropic collapse. Within a year or so, says Pollack, the planet shrinks to a hot ball only a few times its ultimate size. More than 4 billion years later, it is still slowly cooling and shrinking.

"The model can reproduce the observed excess energy for Jupiter right on the button," says Pollack. "So to first order, things make sense." For Saturn, however, the predicted energy loss is a factor of 3 below what Pioneer 11 and ground-based observers have seen. "But it may be that the interior of Saturn is cold enough for hydrogen and helium to become immiscible and separate," says Pollack. As helium falls to the center, it would thus release more gravitational energy as heat.



Wispy terrain on Dione

Is it a mass of cracks rimed with ice?

But there is a problem: this theory also predicts a depletion of helium in the atmosphere, which Voyager's early data seem to be ruling out. Perhaps Voyager's more accurate measurements of Saturn's heat loss will clarify matters.

Toward the end of the catastrophic collapse angular momentum conservation causes the planet to spin very rapidly, adds Pollack. To keep from being torn apart it throws out gas and dust, which form a disk in its equatorial plane. It is here that any satellites and rings form.

All the solid satellites condense from trace elements in the gas of the disk, says Pollack. But the young planet is still quite hot, and vaporizes everything in the inner regions except iron and silicate minerals. So the satellites forming there will be silicate rock and iron. Farther out, the disk is cold enough for water ice or even methane or ammonia ice. Thus the outer satellites will be an ice/rock mixture.

"Jupiter's satellites fit this very nicely," says Pollack. "The closest, Io, is all rock, and the furthest, Callisto, is two-thirds ice with a rocky core."

Eventually, the disk would cool enough to cover all the satellites with ice, says Pollack. Except that things do not get that far. At some time only a few million years after the disk is formed, it disappears.

Perhaps the remaining gas is pulled into the planet by viscous forces. Perhaps it is swept away by the sun in its tau-Tauri phase, during which youthful stars are thought to emit a fierce solar wind. Whatever happens, satellite formation stops, and the solid objects that remain are a record of the temperature distribution in the disk at that time.

This model works very nicely for Jupiter, says Pollack, but at Saturn things become more complicated. For one, Saturn is much less massive than Jupiter (95.2 versus 318 earth masses). So at any given time in its evolution it gives off about one-tenth as much heat.

But perhaps more importantly, calculations indicate that the newly collapsed Saturn was still several times larger than it is now. It spanned the present position of the rings and the orbits of the innermost satellites. Proto-Jupiter, by contrast, lay entirely within the orbit of Io. So just as before, Titan and Saturn's outer satellites should have formed from rock and ice. And within broad limits, this prediction was verified by Pioneer 11.

The inner satellites, however, were cheated of some their rocky material by Saturn itself. The outer layers of the young planet were cool enough for rocky grains to start forming, but dense enough that the grains spiraled inward rather than clumping into satellites. By the time the steadily shrinking Saturn freed up the inner regions, almost the only condensable thing left was water vapor. And by that time Saturn, unlike Jupiter at the same stage, was cool enough to let it condense.

That the satellites and ring particles have icy surfaces was confirmed long ago from ground-based spectra. Their masses were deduced from perturbations in Pioneer 11's trajectory, and their radii from Voyager 1's imagery. So the all-important density measurements are finally in hand: at 1.0 to 1.3 grams per cubic centimeter, the inner satellites of Saturn are indeed made of a little rock and a lot of ice.

Why is Titan the only satellite to have an atmosphere? "Its a question of endowment," says Pollack. Titan formed far enough from the sun—and from Saturn—that it may have acquired not just water ice but a considerable fraction of methane and ammonia ice. At the same time Titan was warm enough for methane and ammonia to have an appreciable vapor pressure, yet massive enough to hold onto them once they had sublimed. Of the other moons in the same size range, Jupiter's Galilean satellites were too warm for anything but water ice (if that), while Neptune's moon Triton is probably too cold for sublimation.

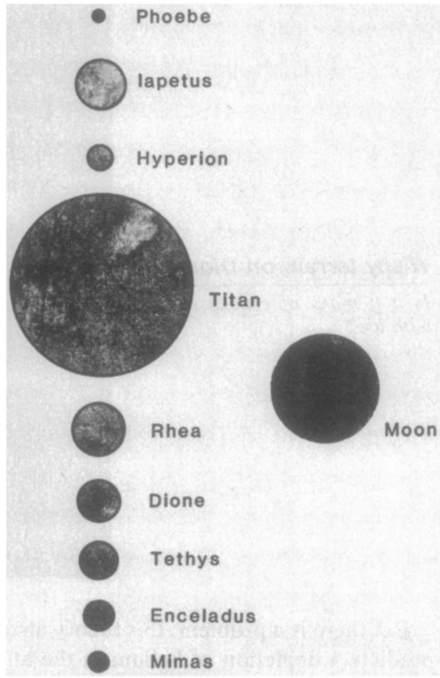
The broad-brush history of Saturn and its satellites that Pollack describes is pretty much the conventional wisdom in planetary science. And for the time being—barring some thunderbolt from Voyager—it will probably stay that way. But clearly, the Voyager data will be filling in a lot of details.

Titan is a case in point. Before Voyager, about the only thing known for sure was that Titan's ultraviolet spectrum showed emission bands of methane. But did this mean a relatively thin atmosphere of pure methane, or a denser atmosphere having only traces of methane within some other gas? Various hypotheses produced widely differing predictions about temperatures and pressure at the surface.

In fact, all the preliminary results from Voyager are consistent with a nitrogen atmosphere containing 1 percent methane or less. Moreover, preliminary measurements of temperature as a function of depth in the atmosphere, extrapolated to the presumed surface of Titan (the low-altitude data will take a while to analyze), suggest a pressure of 1.5 atmospheres and a temperature of roughly 100 K. So liquid nitrogen may also be possible at the surface—although it's a bit early to say whether it lies in puddles, lakes, or oceans.

If Titan's atmosphere really did form from sublimating methane and ammonia ice, as Pollack suggests, it is easy to see where all the nitrogen comes from. Ammonia (NH_3) is quite vulnerable to having its hydrogen knocked off by ultraviolet photons; the hydrogen would escape quickly into space and the fragments would link up into molecular nitrogen.

Meanwhile, methane (CH_4) would also be losing its hydrogen. In this case, however, the fragments would form multicarbon chains: hydrocarbons. Of course, these compounds would be solid at Titanian temperatures; Darrell F. Strobel of the Naval Research Laboratory, a member of the Voyager ultraviolet spectroscopy team, calculates that in 4.6 billion years this high-altitude polymer chemistry has buried Titan's surface to a



The moons of Saturn

From Mimas the innermost to Phoebe the outermost, the satellites are shown here to scale with the Earth's moon.

depth of some 3 kilometers in hydrocarbon snow.

All that any outside observer can see of Titan is an opaque orange smog, which is thought to be comprised of hydrocarbon aerosols. It is still not known whether there exists a distinct layer of liquid nitrogen clouds above the surface. Voyager did find a number of hydrocarbon haze layers in Titan's upper atmosphere and made positive identifications of acetylene (C_2H_2), ethylene (C_2H_4), and ethane (C_2H_6). It also found hydrogen cyanide (HCN). The latter is intriguing, notes Strobel, because in ultraviolet light hydrogen cyanide polymerizes into a complex series of compounds having an overall reddish-brown color. Thus they may be the smog component that gives color to Titan itself.

Once Voyager had confirmed that the inner moons of Saturn are mostly ice, the questions moved quickly into the realm of satellite geology. With masses an order of magnitude smaller than those of Titan or the Galilean satellites of Jupiter, and an order of magnitude larger than those of the asteroid-like moons of Mars, they should fill a major gap in the range of solid bodies that planetary geologists can study.

The named satellites range in size from 140-kilometer-wide Phoebe to 1500-kilometer-wide Rhea and Iapetus. It seems unlikely that any of them are large enough to produce much internal heating on their own, notes imaging team member Torrence V. Johnson of JPL. But ammonia and methane ices have much lower melting points than water ice, and if a satellite contained these compounds in any significant quantity it might be possible to start geological activity with much less internal heating. The cracks, rills, and canyons seen on several of the moons certainly indicate that something is going on.

Voyager's imaging of the satellites, especially its close-ups of Rhea, also show that they have undergone massive cratering. So have all the bodies in the inner solar system. But the cratering on the inner planets was probably caused mainly by Earth-crossing asteroids, whereas the process in the region of Saturn is thought to have been dominated by short-period comets. So careful study of the Voyager satellite photos may illuminate the early history of that part of the solar system.

Voyager 1's major contribution to the understanding of the Saturnian rings will probably lie in the realms of structure and dynamics (see p. 1111). Their reflection spectrum long ago showed them to have icy surfaces, with just enough dust or radiation damage to give them a slight reddish tinge. Voyager will not have anything more to say about composition.

On the other hand, the radio occultation studies, which record the way Voyager's radio beam was scattered as the spacecraft passed behind the rings, will give some indication of particle sizes. Early results show that the translucent C ring, or crepe ring, for example, is composed of icy boulders. Their average size is roughly 1 meter.

The mysterious, ephemeral spokes, which looked dark on the way in, looked bright as Voyager came around Saturn's nightside and headed back out. Such strong forward scattering of sunlight is characteristic of particles having sizes on the order of a few wavelengths of light. The current thinking is that the spokes consist of particles that have somehow become electrically charged and are being lifted slightly out of the rings by electric and magnetic fields.

Atmospheric scientists on the Voyager team went into the Saturn encounter armed with a great many theories developed from Voyager's observations of Jupiter. The big question was whether any of those theories would survive when confronted with conditions on Saturn.

Saturn is roughly the same size as Jupiter and has a similar rotation rate. On the other hand, its surface gravity is lower, it receives less heat from the sun, and it emits relatively more heat from its interior. It has an axial tilt, and thus seasons, whereas Jupiter has neither. Finally, it has the ring shadow, which on the average blocks off 15 percent of the heat that would otherwise reach the equatorial regions.

The most obvious difference between the two atmospheres, Saturn's relative blandness, is partly an illusion. The spectacular turbulence and the variegated cloud patterns are down there, all right. But Saturn's atmosphere is colder than Jupiter's. The clouds form at lower altitudes and thus are obscured by a greater depth of high-altitude aerosols. Moreover, the high, white ammonia clouds, such as those seen on Jupiter, are thicker and more all-encompassing on Saturn.

Still, Voyager did see a number of ovals and streamers that were quite similar to features it had seen on Jupiter. But it also saw fewer of them, especially in Saturn's equatorial zones.

The first priority for the Voyager scientists will be to map the zonal winds of Saturn. That is a tedious job; it involves plotting the relative motion of hundreds of individual spots. Voyager spent hours taking time-lapse movies of Saturn's atmosphere for just this purpose.

On Jupiter the mapping revealed a remarkable series of alternating east-west jet streams, some reaching speeds of 100 meters per second. Records of earth-based observations show that this pattern has remained stable for more than 70 years. Moreover, the Voyager plots show a strong symmetry in the wind patterns between the northern and southern hemispheres. Andrew Ingersoll of Caltech believes that the stability and symmetry of the zonal winds may arise from some global process deeper in the interior of the planet, although no one can say what that process might be.

The earliest Voyager results, however, are suggesting that the whole picture may be different on Saturn. The equatorial winds on Saturn move eastward at some 500 meters per second, five times faster than anything on Jupiter. Moreover, they exhibit a uniform, symmetrical decrease to the north and south, reaching zero at the 40° latitudes. They then begin to blow eastward again at higher latitudes. The winds of Saturn, it seems, have no reversals.

One of the most direct ways to learn about Saturn's deep interior, paradoxically, is to back off into space and examine its magnetic field. Pioneer was the first to do this. It found a very symmetrical dipole field with a strength much like that of the earth and tilted less than 1° from Saturn's rotation axis. The first two points suggest that Saturn's core of metallic hydrogen is relatively small.

But the final point is harder to understand. Everything else in nature that produces a magnetic field, from the earth to Jupiter to a neutron star, has its dipole axis significantly tilted from its rotation axis. Moreover, the earth's field has reversed hundreds of times and has always come back tilted. So why is Saturn's field such a straight arrow? Is it in the middle of a reversal itself?

At any rate, the field is not utterly symmetrical. Voyager made the first accurate determination of Saturn's rotation rate—a very difficult thing to do with a planet that has no solid surface—by detecting bursts of radio waves with a 10 hour, 39 minute, 26 second periodicity. Presumably these bursts were emitted by charged particles trapped in an anomaly of the field. But all that could be said about that anomaly from the early data was that the power of the bursts was about 50 billion watts, that their peak frequency was about 175 kilohertz, and that they came from somewhere in the auroral regions around the north Saturnian pole.—M. MITCHELL WALDROP

Rings Within Rings Within Rings Within . . .

Theories already proposed for the Uranian rings could explain much of the odd behavior of rings and satellites around Saturn

The myriad of ringlets discovered around Saturn by Voyager 1 dazzled researchers and the public alike, but the least astonished seem to be specialists in the dynamical mechanics of rings. They respond to reported concerns about the applicability of known physical laws with calm reassurances. "Don't worry about Newton's equations," one says, "most people don't realize how many solutions they have." In fact, an explanation previously advanced for the perplexingly narrow rings of Uranus also explains the narrowest rings of Saturn and may account for the grooved, "phonograph" appearance of the major rings' subdivisions. Theoreticians also found a sound explanation, which was most recently applied to Uranian ring theory, for the Saturnian satellites that appear to be on a perpetual collision course.

Traditional theories that explain the appearance of Saturn's rings as seen from Earth have not been abandoned, but new Earth-based and spacecraft observations, Voyager being only the latest, have revealed new features that cannot possibly be explained by them. Left to themselves, the billions of orbiting bodies that make up Saturn's rings would settle into a smooth, uninterrupted disk above the equator because of the gravitational effects of Saturn's equatorial bulge. But even 140 years ago, observers using telescopes could make out two gaps in the disk, one between the outer A and B rings (the Cassini division) and a smaller one within the A ring (the Encke division).

Theoreticians suggested that gravitational effects of known satellites beyond the rings created and maintain these apparently empty gaps in the disk. The moons and the gaps are linked, according to the theory, because any particles that might have been orbiting within the Cassini division, for instance, would complete exactly two orbits in the time it takes the moon Mimas to complete one orbit. Being in such an orbital resonance with Mimas, the particle would repeatedly encounter Mimas's relatively large gravitational field at the same points in its orbit and be swept out of the way. This explanation is still the best available for the major divisions, although dynamicists have always conceded that it may not be the only process keeping the gaps open.

That explanation was fine until observers found more divisions than theorists had resonances. Last year, the Pioneer 11 spacecraft found another gap in the A ring and a relatively narrow ring (less than 800 kilometers wide) just outside

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