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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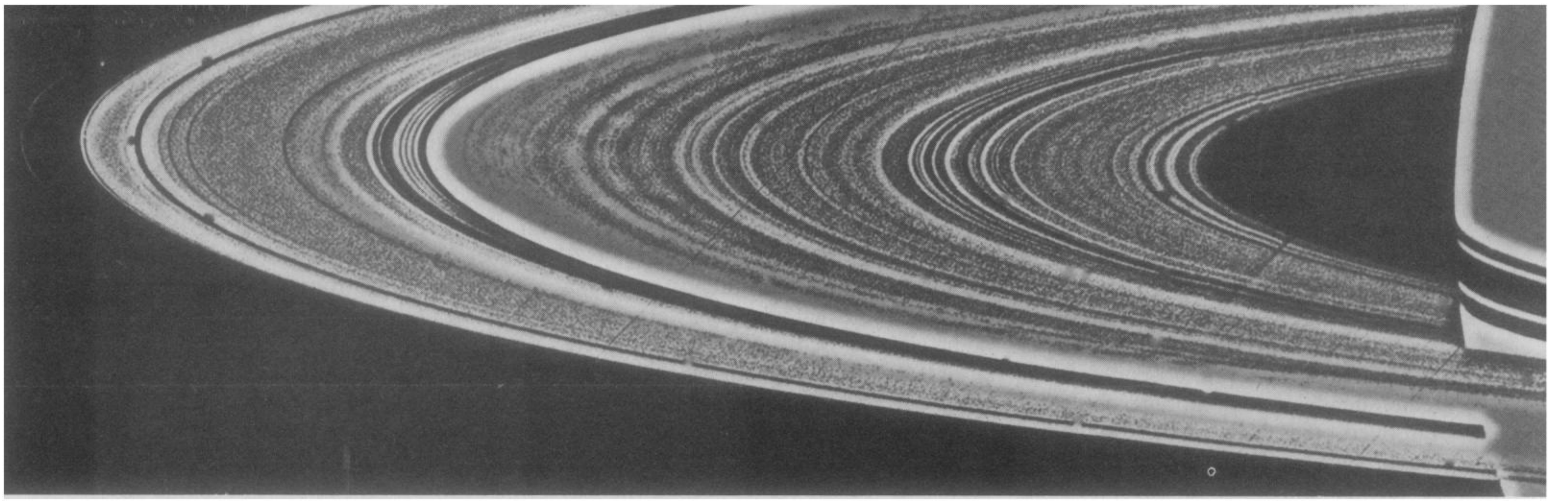
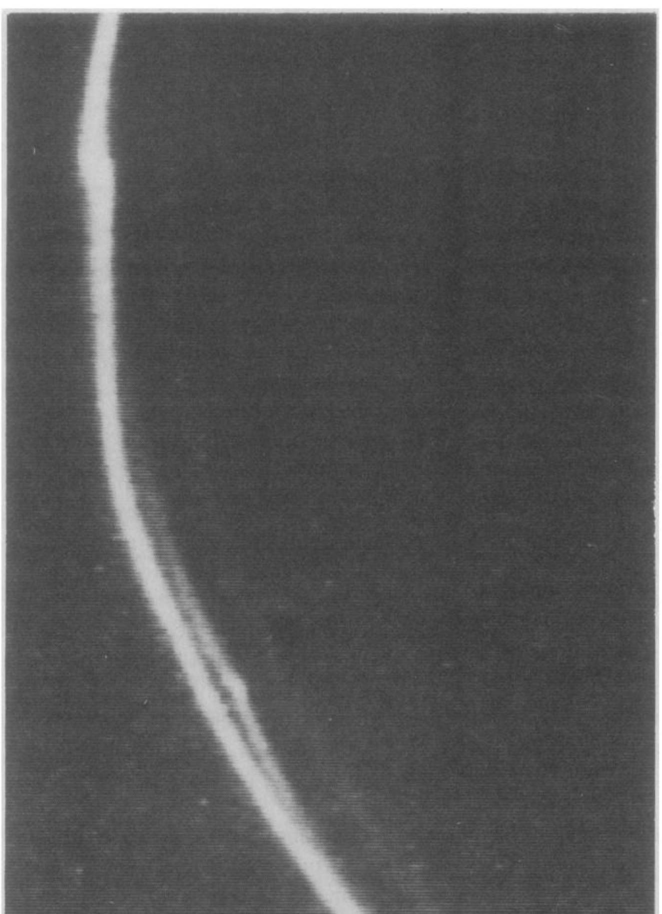


Voyager's enhanced-contrast view of Saturn's rings

Approximately 95 individual rings can be seen in this Voyager image made while 8 million kilometers from Saturn. From the outside in, Voyager recorded the hairline-thin F ring and one of its confining satellites (both of which may be too faint to show up in this reproduction), the A ring containing the dark Encke division, the Cassini division and its compact set of four rings, the B ring, and the C ring. [NASA photograph]

the A ring, and confirmed a light veil of particles unevenly filling the Cassini division. Then Earth-based observers verified the existence of the faint E ring, extending to four times the breadth of the three classic rings. Voyager 1, with a view 6000 times sharper than that possible from Earth, struck a final, devastating blow to resonances as the only cause of rings. The three classic rings seemed to explode into hundreds of ringlets. The most recent quotable number was "perhaps 500 to 1000," but no one has yet had the time or patience to make a complete count. The Cassini division alone split into four broad rings bounded by two strong gaps. One particularly narrow ring in a C ring gap sticks out from its neighbors because it is elliptical rather than circular and its width varies around its circumference. The most outlandish ring so far is Pioneer 11's F ring, which Voyager resolved into three rings 30 to 50 kilometers wide, two of which appear to be interwoven.



Saturn's F ring

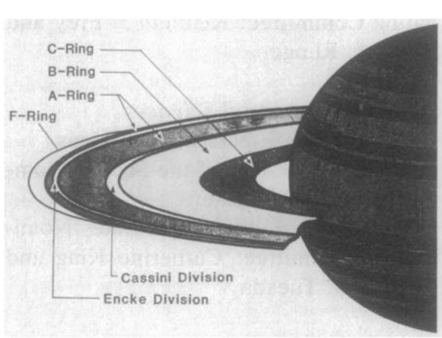
Located immediately outside of the main rings, the F ring is actually three rings, a faint ring about 35 kilometers across and two narrower rings that appear to be braided or interwoven and at places kinked. Most speculations about their behavior involve differences in particle sizes. [NASA photograph]

Researchers now agree that resonances with moons outside the main rings are too few and too weak to form most of these features directly. The Cassini and Encke divisions are still linked to resonances in most researchers' thinking, but even in these major divisions other forces may need to be postulated to account for the sizes and emptiness observed. Some new evidence of external control through resonances, limited though it may be, has been found in Voyager images of the A ring, according to Jeffrey Cuzzi of NASA's Ames Research Center at Moffet Field, California. Two small satellites (S10 and S11), both Voyager discoveries, seem to be clearing a recognizable pattern of narrow gaps in the A ring at the proper spacings relative to the satellites' orbits outside the F ring.

Aside from these few resonance-controlled features, theoreticians believe that the appearance of Saturn's main rings are probably controlled by the gravity of bodies within the rings themselves. At the moment, the most favored way of doing that for the main rings is the same as that proposed to hold the tiny F ring and, probably, the rings of Uranus together—small satellites orbiting nearby on either side of a ring.

Peter Goldreich of the California Institute of Technology and Scott Tremaine of the Institute for Advanced Study in Princeton suggested this arrangement as the confining mechanism of the nine narrow rings of Uranus after the rings' chance discovery in 1977. They reasoned that such satellites could thwart the tendency of the smaller particles to drift out of their ringlet by gravitationally plowing them aside. How a force of attraction can act to repel another body is not intuitively obvious to one not trained in the field, perhaps because the mechanism depends on the presence of many ring particles that can often collide with each other. Changing a particle's angular momentum and thus its orbit depends on its having collisions or gravitational interactions with other particles. This physics involving many colliding particles sets the study of ring dynamics apart from classic celestial mechanics, in which few or no collisions are assumed, and fluid dynamics, in which much more frequent collisions are known to occur than in a ring.

Although their reasoning appeared to many to be sound, Goldreich and Tremaine could not prove that their mechanism is working around Uranus because the 1-kilometer moons that they predicted would be confining the rings cannot be detected from Earth. But Voyager 1

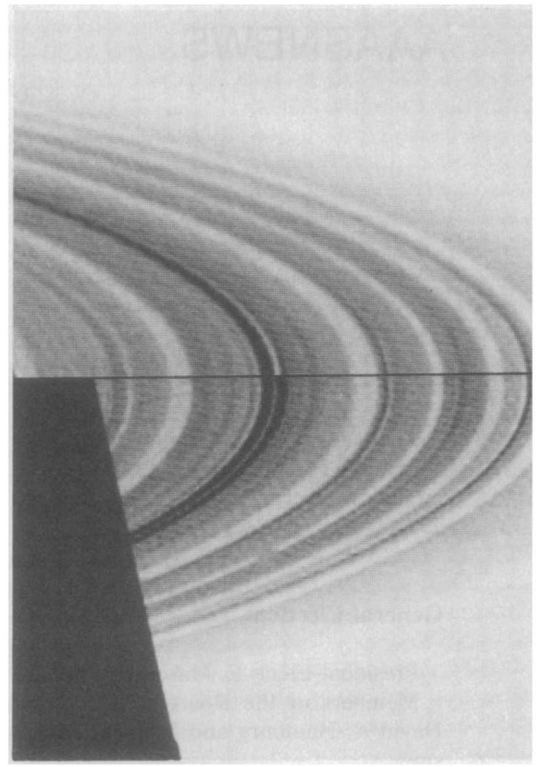


has greatly strengthened their argument by finding a narrow ring, the F ring, and its confining satellites (S13 and S14) around Saturn. The elliptical ring in the C ring gap also appears to be a Uranian-type ring, as does one in the Cassini division, although no confining satellites were found. As a clincher, Voyager's third satellite discovery, the 150-kilometer-wide 15th moon of Saturn, seems to be keeping the outer edge of the A ring sharp by herding in ring particles from its orbit 800 kilometers beyond the ring edge.

Herding by satellites or larger than average ring particles (if the two can be distinguished any longer) seems to be a widespread phenomenon and may explain most of Saturn's and Uranus's ring structure. But the F ring, at least, is not as well behaved as the Uranian rings that originally inspired the theory. Rather than a single, smooth curve, the F "ring" is actually three rings only a few tens of kilometers wide, two of which often have sharp kinks and appear to be "braided" about each other. Although the actual geometrical relationships of these rings are still to be worked out, researchers are certain that the Uranian rings are not so unruly. By measuring the light of stars passing behind them last March and again in August, James Elliot of the Massachusetts Institute of Technology found that the Uranian rings are 3 to 60 kilometers wide with edges less than 1 kilometer wide. The only variation detected within a ring was a concentration of particles near the edge of the 60-kilometer ring. These observations, thanks to the minute apparent size of the stars that the rings occulted, are more precise, Elliot says, than any that Voyager could make if it arrives at Uranus in 1986 as hoped. Goldreich and Tremaine report that the sizes and shapes of the Uranian rings fit an elliptical model within 3 kilometers. The same would not be true of the F ring, they say.

No one has any ready explanations of the less than ideal details of the F ring, but there are some possibilities. Goldreich notes that the herding satellites, being vastly larger than those suggested for Uranus, should set up waves in the rings, which could explain some of their irregular shapes but not the sharp kinks. The multiple strands, he says, might result from different reactions to gravitational effects by particles of different sizes. Independently, Bradford Smith of the University of Arizona has suggested that the microscopic particles of the F ring, whose presence was evidenced by the ring's brightness when back-lighted, might become electrically charged by radiation and then pushed about by Saturn's magnetic field. Jupiter's magnetic field appears to actually throw particles out of its ring plane in that way, as first suggested by David Jewitt of Caltech.

Theoretical studies of the rings of Uranus include an explanation of another curious phenomenon encountered by Voyager, the co-orbiting satellites. These small, irregularly shaped satellites, first glimpsed from Earth, occupy different points on the same orbit. One is now slowly gaining on the other, so that a collision would appear inevitable. No one expected that to happen, but how it could be avoided was not immediately apparent except to a small group of specialists. The answer, most dynamicists agree, is that the gaining satellite will behave just as Stanley Dermott and Thomas Gold have suggested Uranian ring particles act. Instead of colliding, the gaining satellite will reverse its motion relative to its mate and move back along their orbital path, appearing to lose ground to the other as they both whiz



An elliptical ring within the C ring

The noncircularity of a narrow ring in a gap (the black band) of the C ring (the gray area inside the overexposed B ring) was highlighted by juxtaposing images from opposite sides of the rings. Thus, only the elliptical ring fails to match up and the varying ring width becomes obvious. [*NASA photograph*]

around Saturn. Eventually, it will describe a horseshoe-shaped path with respect to the other satellite. Some dynamicists have doubts whether a million ring particles could do that but they see no problems with one large particle doing it.

Although the rings of Saturn may not be quite as mysterious as reported at first, much work remains for the small group of theoreticians that devote even a part of their time to ring dynamics. In addition to the structure of the main rings, Voyager reliably detected the inner D ring and its structure for the first time. Ground-based observations suggest to some that the broad outer E ring may consist of geologically young material blasted off the satellite Enceladus. And the renowned "spokes" of the B ring, fingers of darkness or brightness radiating across the ring, may require some attention, although any explanation is generally believed not to involve dynamics. Aside from satisfying their curiosity, researchers believe that studies of rings should shed some light on how the diffuse ball of gas and dust, from which the solar system formed, could have been subdivided and concentrated to produce planets, moons, asteroids, comets, and ring systems themselves.

—RICHARD A. KERR