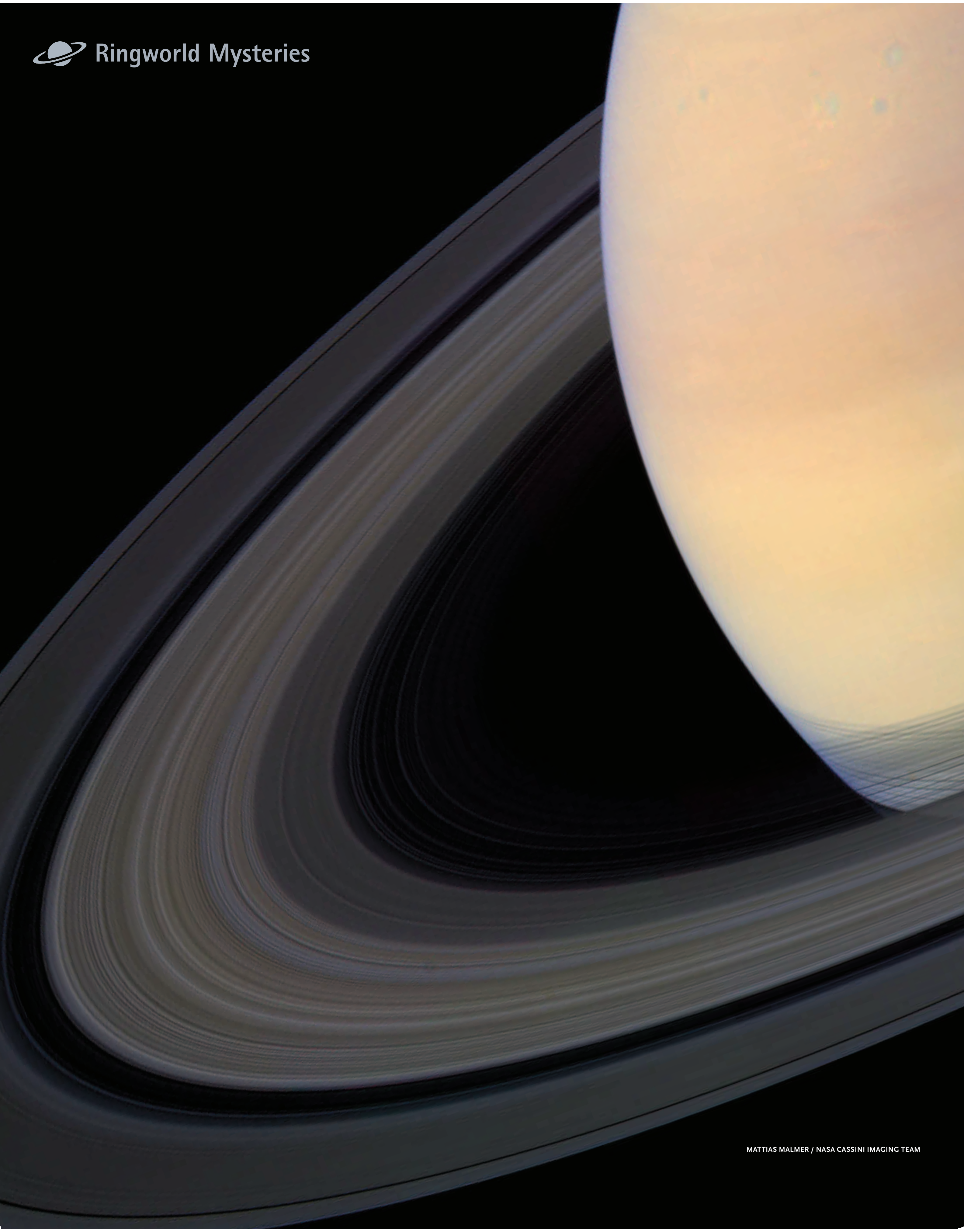


MATTIAS MALMER / NASA CASSINI IMAGING TEAM

Saturn's amazing Rings

J. Kelly Beatty

Astronomers' understanding of these beautiful bands has come a long way since Galileo first spied "a case so surprising" in 1610.

MANY OF US got our first big celestial thrill by peering into an eyepiece at the planet Saturn. This month the ringed wonder has again positioned itself for easy telescopic viewing, as Alan MacRobert explains on page 50. But no matter how good the telescope, views of Saturn's rings from Earth are no match for what spacecraft have revealed with close-range inspection.

Future space historians will recall two great epochs of discovery concerning Saturn. During the first, in 1980–81, Voyagers 1 and 2 revealed that the planet's stunning ring system is not a single smooth sheet but rather consists of thousands of individual ribbons, at once beautiful and strange in their collective organization. In the second, beginning in mid-2004, NASA's Cassini orbiter found the rings to be even more beautiful — and stranger — than we'd previously imagined.

It's no accident that the images returned by Cassini are dramatically otherworldly. Carolyn Porco (Space Science Institute) says that when she was chosen to head the mission's imaging team, "I knew I was going to make singular use of the camera and pay a lot of attention to how its images would be presented to the public." Porco has always had a soft spot for Saturn's elegant bands — she picked up the nickname "Ring Lady" while researching ring dynamics for her doctoral thesis.

Cassini has certainly been busy. Since the spacecraft's arrival at Saturn its wide-angle and telephoto cameras (just one of 12 experiment packages) have snapped an astounding 285,000 frames. But there's a lot of territory to cover: the planet's three "classic" A, B, and C rings have a combined area of roughly 40 billion square kilometers (15 billion square miles), nearly 100 times Earth's surface area.

So what's been learned since Cassini became Saturn's first artificial satellite? As Porco sums it up, "We've come to understand how the rings behave if left to themselves." Their behavior is often chaotic and unpredictable, with a structure much more complicated than astronomers expected. "There's a lot going on," says Jeffrey Cuzzi (NASA/Ames Research Center). "The rings are changing before our eyes."

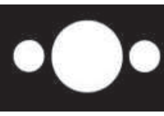
The last few years have witnessed an explosion of new revelations about Saturn's beautiful bands, and this article will recap some of those findings, from the outside inward.

Dynamic Dust

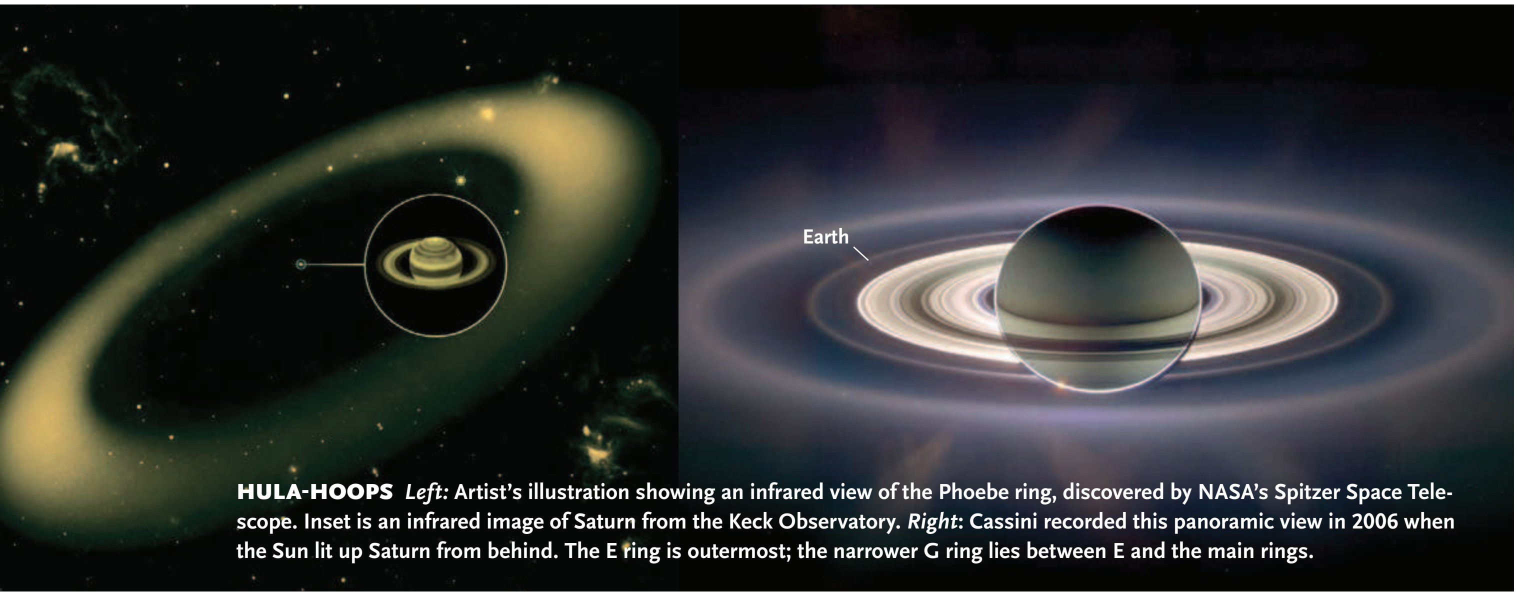
In 2009 astronomers used deep-infrared scans by NASA's Spitzer Space Telescope to detect a tenuous yet enormous doughnut of ring material 6,000,000 to 12,000,000 kilometers from Saturn — 50 to 100 times the planet's diameter. It extends all the way out to dark little Phoebe, an oddball moon just 215 km (135 miles) across that moves in a retrograde orbit tipped roughly 28° to Saturn's equator.

Apparently, impact debris that has escaped from Phoebe is being dragged toward Saturn by subtle gravitational and radiational forces. Some of this dust gets swept up by the next moons inward, particularly the leading hemisphere of Iapetus and (probably) all of Hyperion. It strikes Iapetus at very high velocities, "like bugs on a car's

RINGWORLD Mattias Malmer pieced together this mosaic of Saturn and its rings from 102 frames recorded by NASA's Cassini spacecraft in October 2004. Cassini's observations reveal wondrous and delicate details, from ringlets hiding in "empty" gaps to kilometer-long spikes gravitationally splashed out by passing moonlets.



A drawing of Saturn by Galileo Galilei made in 1610



HULA-HOOPS *Left:* Artist's illustration showing an infrared view of the Phoebe ring, discovered by NASA's Spitzer Space Telescope. Inset is an infrared image of Saturn from the Keck Observatory. *Right*: Cassini recorded this panoramic view in 2006 when the Sun lit up Saturn from behind. The E ring is outermost; the narrower G ring lies between E and the main rings.

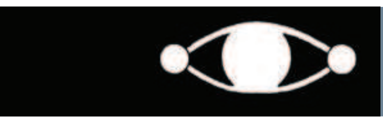
LEFT: NASA / JPL / KECK; RIGHT: NASA / JPL / SPACE SCIENCE INSTITUTE

windshield," observes Douglas Hamilton (University of Maryland), and helps explain why the moon is strikingly two-faced, with its leading hemisphere black as coal and a backside that's icy white (*S&T:* June 2009, page 26).

The Phoebe ring joins a growing list of Saturnian bands created by moons embedded within them. For example, Cassini captured a cluster of geysers near the south pole of Enceladus dramatically spewing particles into space, and these spread out to form the E ring (*S&T*: March 2006, page 38). The spacecraft has also spotted faint rings centered on the orbits of Pallene and the co-orbiting moonlets Janus and Epimetheus, as well as partial rings, or "arcs," extending to either side of the tiny moons Methone and Anthe.

But these interactions are all tame compared with the shenanigans of the F ring, a dusty sibling located just outside the A ring (see image at top of facing page). Voyager photographs of this ring showed tortured twists and kinks that left mission scientists slack-jawed in disbelief.

It's clear now that the F ring has a relatively dense core that's accompanied by thinner bands full of waves and ripples. Much of this structure is driven by repetitive gravitational yanks, primarily from the tiny moons Prometheus and (to a lesser extent) Pandora, which circle just inside and outside of it, respectively. But there's much more going on. Cassini images taken last year reveal clusters of elongated streaks — some up to 250 km long — jutting from the F ring. Apparently these "minijets" are being dragged along by giant snowballs, roughly 1.5 km across, that are moving unseen within the dense core.



A sketch of Saturn by Francesco Fontana made in 1646

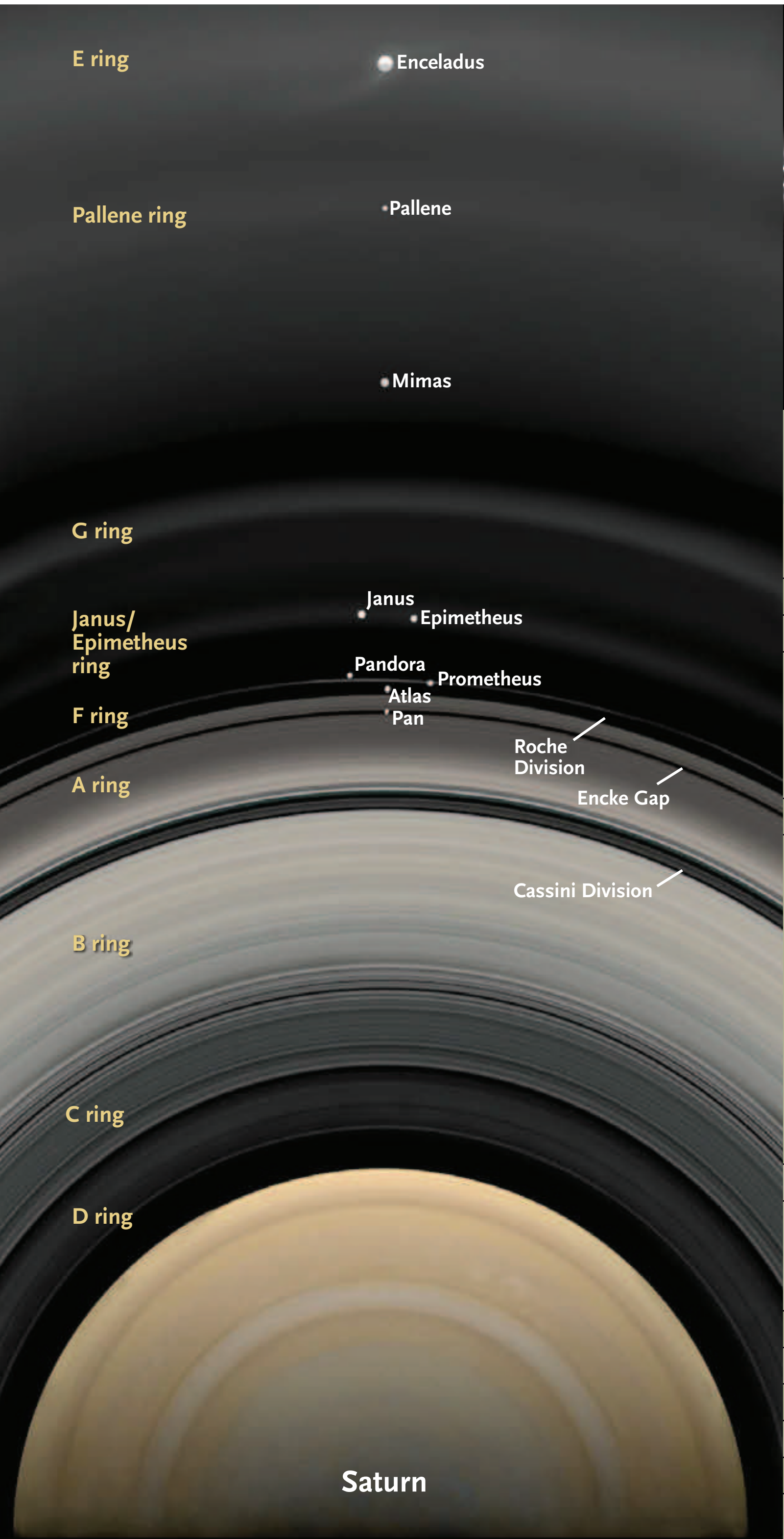
All this jostling can't have been going on for more than a few million years. "My own suspicion is that the F ring is a relatively recent addition to the ring system and may be the result of the collisional breakup of a small moon — perhaps one that formed in the disk and migrated outward," suggests Carl Murray (Queen Mary University, England).

Prior to the arrival of the Voyagers and Cassini, dynamicists imagined that gentle jostling among all the icy bits in the main A and B rings would tend to smooth out localized clumps and fill any voids. But when spacecraft images revealed thousands of discrete ringlets, such thinking had to change. Instead, there's a newfound appreciation that ring particles prefer to act collectively rather than individually.

Those in the A and B rings range from centimeters to meters in size, and computer modeling suggests that they often come together in loosely bound clumps that quickly break apart. Then, rather than scattering randomly, the bits peel off in upstream and downstream wakes created by Keplerian shear: those closest to the planet orbit a little faster and creep ahead of the main clump, while those on the outer edge trail behind it.

These *self-gravity wakes* appear to be ubiquitous throughout the A and B rings, and dynamicists think these same structures should be present in the protoplanetary disks surrounding newly formed stars and perhaps even in galactic arms. "We knew self-gravity was important all along, but it was beyond our observational capability," says Cuzzi. However, mission scientists could still "see" the wakes by having Cassini direct its radio beacon through the rings en route to Earth, which it has done hundreds of times in the past 9 years. "It's like taking a 3-D CAT scan of these structures," he explains.

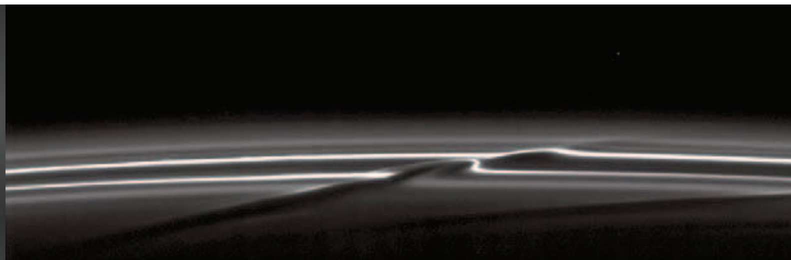
Another kind of organized bulk motion is related



RUBBLE PILE According to one estimate, there are 10 million trillion (10^{19}) ring particles at least 1 cm across in Saturn's three main rings.

PRECISION AND ORDER Spanning hundred of thousands of kilometers, Saturn's rings are highly structured, as shown in this (roughly to scale) illustration. The D ring orbits only a few thousand kilometers above the planet's atmosphere.

DON DAVIS

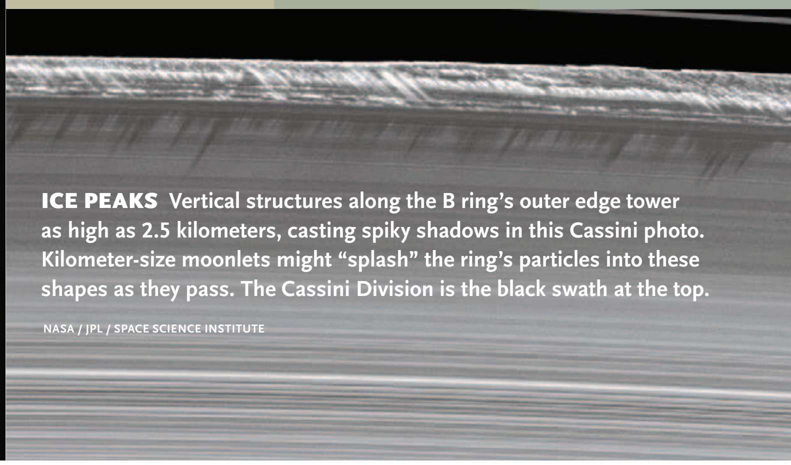


WARPED PERSPECTIVE An image taken by Cassini in September 2008 shows striking distortions in Saturn's F ring (seen from its unilluminated side). These irregularities are created by close approaches of the moon Prometheus, which has a slightly eccentric orbit.

NASA / JPL / SPACE SCIENCE INSTITUTE

A System Like No Other

Feature	Distance from Saturn's center (km)	Radial width (km)
D ring	67,000 – 74,490	7,500
C ring	74,490 – 91,980	17,500
Colombo Gap	77,800	100
Maxwell Gap	87,500	270
Bond Gap	88,690 – 88,720	30
Dawes Gap	90,200 – 90,220	20
B ring	91,980 – 117,500	25,500
Cassini Division	117,500 – 122,050	4,600
Huygens Gap	117,680	285 – 440
Herschel Gap	118,183 – 118,285	102
Russell Gap	118,597 – 118,630	33
Jeffreys Gap	118,931 – 118,969	38
Kuiper Gap	119,403 – 119,406	3
Laplace Gap	119,848 – 120,086	238
Bessel Gap	120,236 – 120,246	10
Barnard Gap	120,305 – 120,318	13
A ring	122,050 – 136,770	14,700
Encke Gap	133,570	325
Keeler Gap	136,505	35
Roche Division	136,770 – 139,380	2,600
F ring	140,224	30 – 500
Janus/Epimetheus ring	149,000 – 154,000	5,000
G ring	166,000 – 174,000	8,000
Pallene ring	211,000 – 213,500	2,500
E ring	180,000 – 480,000	300,000
Phoebe ring	~6,000,000 – ~12,000,000	~6,000,000



ICE PEAKS Vertical structures along the B ring's outer edge tower as high as 2.5 kilometers, casting spiky shadows in this Cassini photo. Kilometer-size moonlets might "splash" the ring's particles into these shapes as they pass. The Cassini Division is the black swath at the top.

NASA / JPL / SPACE SCIENCE INSTITUTE

to how collisions transport angular momentum in the rings. Normally, explains Heikki Salo (University of Oulu, Finland), ring material quickly flows away from dense regions and toward sparse ones. However, in close quarters the velocities of individual particles can become damped, or slowed, causing pileups. The result is a kind of resonant "splashing" between closely separated ringlets — not unlike the back-and-forth wave action seen in a bathtub or swimming pool.

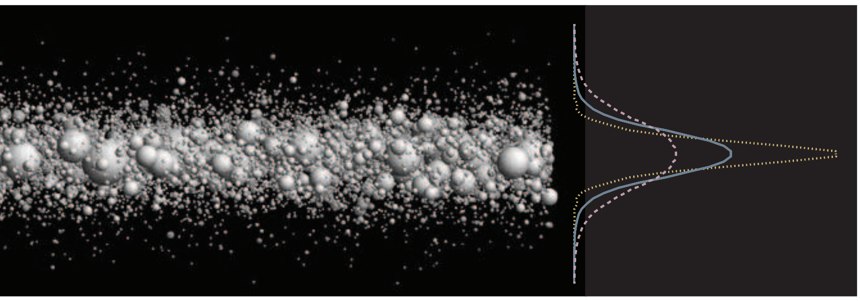
Strokes, Spokes, and Pokes

One of the most curious ring discoveries involves localized twists of icy rubble dubbed "propellers" because of their distinctive twin-lobed shape (see image at right). Cornell University researcher Matthew Tiscareno has intently followed these curious features since their discovery by Cassini in 2006. He's concluded that their twin "blades" appear to be voids or concentrations of ring particles, either of which can look bright against the background around them. Predicted to exist even before Cassini's arrival, propellers are apparently caused by tiny embedded moonlets roughly 300 meters across. These are too small to be resolved in images, but they're massive enough to disturb the flow of particles in their vicinity.

Cassini's cameras have spotted thousands of propellers in three narrow zones within the A ring, yet so far only one has been spotted in the B ring, where the particles are packed much closer together. The biggest propellers, which are thousands of kilometers long and have nicknames that honor early aviators, occupy a strip between the Encke Gap and the A ring's outer edge.

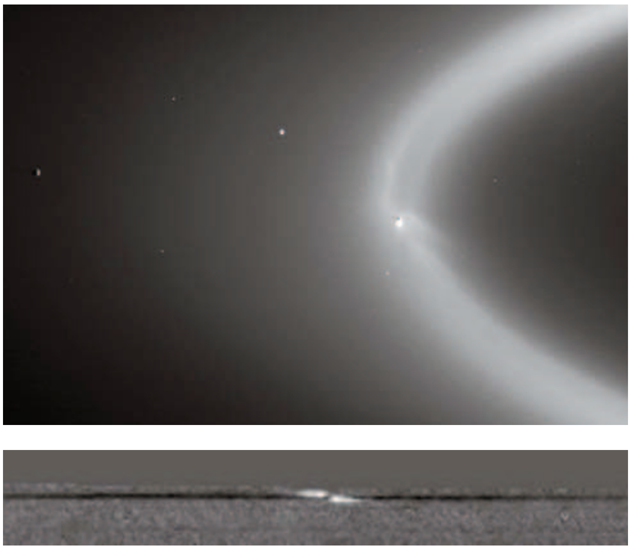
The one dubbed Blériot (for French aviation pioneer Louis Blériot) isn't particularly well-behaved. It some-

STACKED DECK Despite their enormous size, Saturn's rings are incredibly thin — no thicker than about 10 to 20 meters in most places. In this edge-on simulation, the largest particles (at least 1.7 meters across) cluster near the ring's midplane; the yellow curve at right shows their distribution. But mid-size (blue curve) and small (pink curve) particles "float" somewhat, creating slightly thicker layers.



HEIKKI SALO

A sketch of Saturn by Christiaan Huygens made in 1655



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FOUNTAINHEAD *Top:* Saturn's moon Enceladus, seen at center, is the source of the E ring. Gas-fueled geysers constantly jettison ice crystals into space. *Bottom*: This propeller-shaped disturbance in Saturn's A ring, nicknamed Blériot, is created by a moon too small to be resolved. Disturbed ring material close to the moon reflects sunlight brightly and thus appears white.

times precedes or lags its expected position by hundreds of miles. Maybe the responsible moonlet is being swayed by the gravitational influence of another, larger moon, or perhaps it's being bumped and jostled by rogue waves in its vicinity. Either way, Tiscareno says, "It's actually quite astounding." Ring specialist Joseph Burns (Cornell University) adds that it's the kind of jerky migration dynamicists would expect to see on a much larger scale when just-forming planets start growing in stars' protoplanetary disks (see page 26).

Meanwhile, in the B ring, researchers are still trying to understand the furtive features called spokes. First photographed by Voyager 1 in 1980 (though reported by a few visual observers before that), these dusky streaks appeared dark against the bright ring as the spacecraft approached. But they looked bright in images taken when looking at the planet with the Sun behind it, implying that they consist of microscopically fine dust particles that scatter light strongly at large angles, much like dust on a car windshield (*S&T*: February 2007, page 32).

Typically, spokes materialize in a few minutes as radial streaks in the B ring, then smear out as they shear apart due to the differential orbital speeds along their lengths. Spoke activity can be absent for years at a time, yet it seems to peak when the ring plane is nearly edge-on as seen from the Sun during Saturn's 29½-year orbit (most recently in 2009).

Theorists quickly seized on the idea that these quickly forming spokes are triggered by some kind of episodic disturbance in the planet's strong magnetosphere. No physical motion can cover such large radial distances

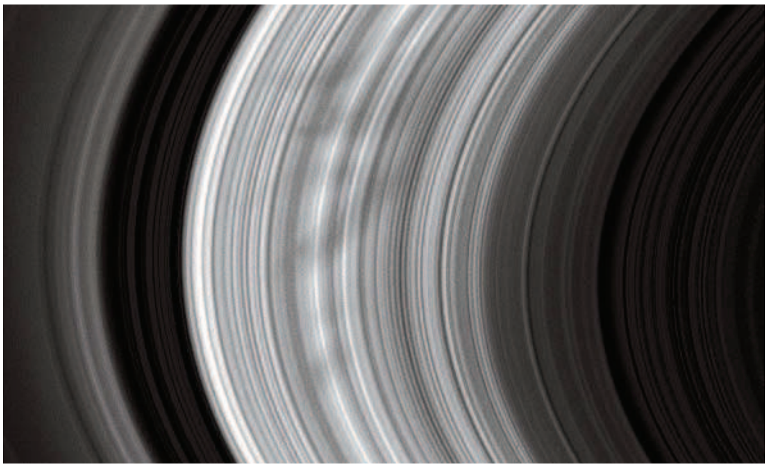
HOW BIG?
Saturn's "classic" A, B, and C rings span 70% of the Earth-Moon distance and have nearly 100 times the surface area of Earth.

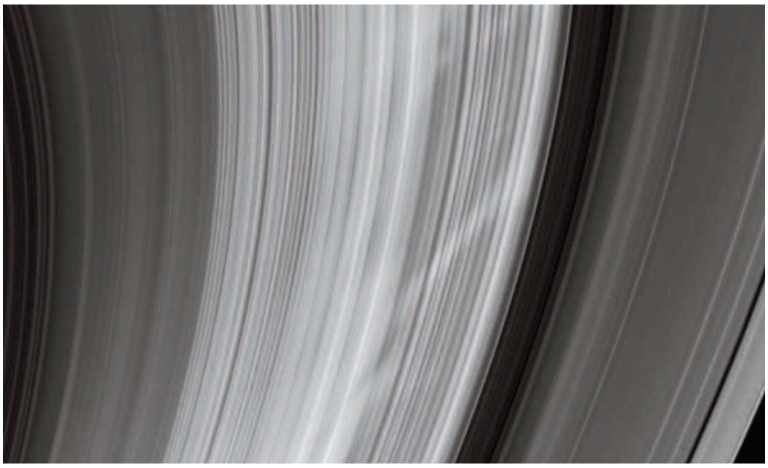
so quickly, but Saturn's strong magnetic field flows through the rings all the time. Most proposed explanations either assume that elongated dust grains somehow become charged and aligned with the planet's magnetic or electric fields or that microscopic grains pick up an electrostatic charge strong enough to levitate them rapidly out of the ring plane.

One widely accepted model, put forward by Christoph Goertz and Gregor Morfill in 1983, argued that meteoritic impacts generated rapidly expanding plasma clouds that charged and levitated the dust. But several years ago follow-up analysis showed that the plasma couldn't spread fast enough to match some spokes' rapid onset.

"Despite 30 years of work, there are no models for spoke formation that fully satisfy all of the observations," says Daniel Jontof-Hutter, an interplanetary-dust specialist at NASA's Ames Research Center.

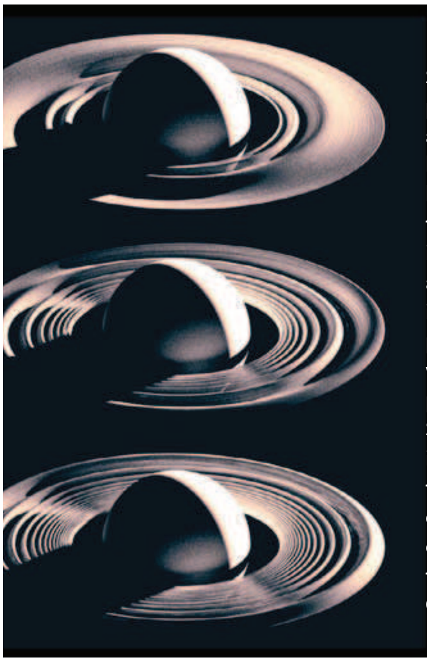
Still, the notion of an impact-induced trigger has merit, and Jontof-Hutter is pursuing an idea put forward a few years ago by Hamilton. It's still a work in progress, but Hamilton's basic concept is that a meteoroid strikes the B ring, releasing a cloud of charged particles. These are quickly accelerated out of the ring plane by gravity and electromagnetic forces, which slam them back into the ring at high speeds in some other location, generating more debris. This collisional cascade would stretch to cover a wide radial range in the ring but be rather confined in longitude, Jontof-Hutter explains, matching the





NASA / JPL / SPACE SCIENCE INSTITUTE (2)

DUSTY MIRAGES? The dark, shadowy fingers known as "spokes" in Saturn's B ring remain a puzzle to ring specialists. They appear bright (*bottom*) when seen in forward-scattered light; this implies that the dust particles in them are quite small.



HEIKKI SALO

RIPPLE EFFECT Scientists suspect that in 1983 a large meteoroid broke up just before striking the C ring. The impact caused a localized tilt in the ring that propagated outward as its nodes precessed around Saturn, as shown in this simulation. This action created a series of subtle corrugations detected in Cassini images.

The Cassini Division

Although the big gap between Saturn's A and B rings appears black and empty from Earth, it's not. In fact, the Cassini Division (named for Jean-Dominique Cassini, who discovered it in 1675) is full of interesting features — including eight narrow gaps that really *are* empty.

Dynamicists don't really know why the Cassini Division exists. They've known for decades that the B ring's outer edge is defined by a strong orbital connection with the moon Mimas. Particles there travel around Saturn exactly twice in the time that Mimas orbits once, and because of this resonance the boundary has a decidedly oval shape.

Calculations by Valéry Lainey (IMCCE, Paris) and others suggest that the orbit of Mimas is slowly collapsing inward, thanks to a slight forced eccentricity due to neighboring Tethys and gravitational perturbations by Saturn. If the researchers' preliminary conclusions hold up, then Mimas has been moving closer to Saturn by about 2 mm per day over the past 20 million years — and so has the outer edge of the B ring. Assuming the inward migration has been ongoing continuously, a gap as wide as the Cassini Division could have formed in less than 10 million years.

sharp radial edges along which spokes seem to form.

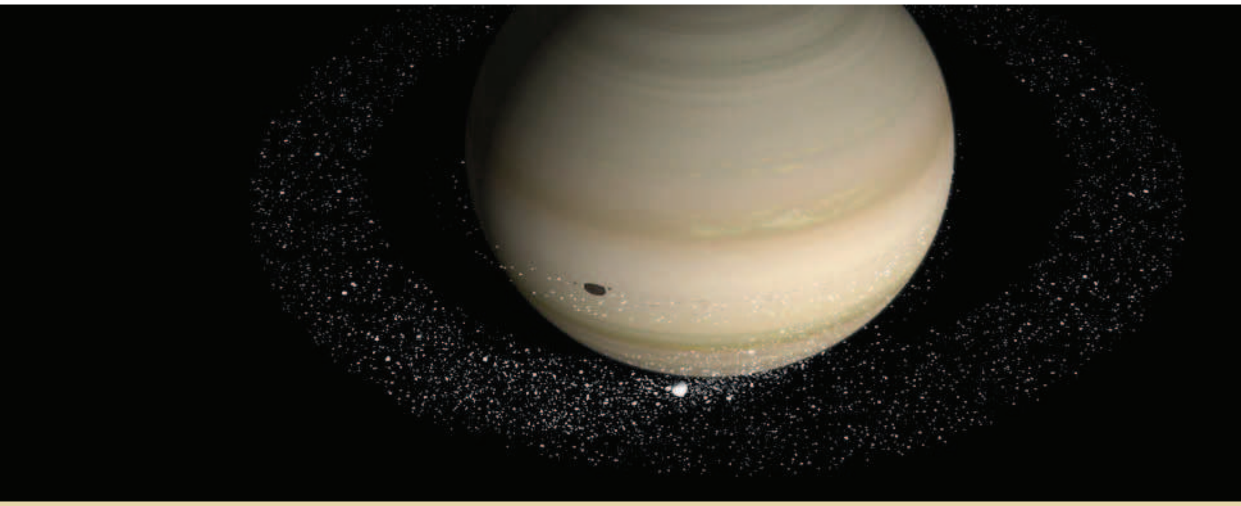
The rings are occasionally hit by interplanetary projectiles, with interesting consequences. In August 2009, when the ring plane was almost exactly edge-on to the Sun, a team led by Cornell's Matthew Hedman spotted a subtle corrugation in Cassini images that extended across the entire C ring. The ripples were separated by 30 to 80 km and ranged from 2 to 20 meters tall. But the edge-on illumination accentuated their presence by creating long, distinct shadows.

Hedman's team concluded that the corrugation was a "splash pattern" of sorts caused by the impact of a billion-ton debris cloud — not a single object, but instead something that had broken apart on its way in. The impulse of kinetic energy had caused a localized tilt in the ring, which then got torqued around in longitude by Saturn's uneven gravity field. Over time the vertical warping became wound up like a watch spring as it extended throughout the C ring. By "unwinding" the corrugation backward in time, the researchers concluded that the ring likely took the hit around September 1983. Smaller impacts likely happen all the time.

Jean-Dominique Cassini's sketch showing his division, made in 1676

The End Game

Ultimately, planetary scientists would like to solve the centuries-old puzzle of how Saturn's ring system came to exist (see below). But a critical missing piece is knowing how much mass is hiding in those beautiful bands and, specifically, in the dense, optically opaque B ring. Right now there's no way to know for sure — it might be 10^{17} tons (a couple of Mimas's worth), but all that clumping due to



MOON DEBRIS Saturn's rings perhaps formed when a large moon ventured too close to the young planet and was stripped of its icy outer layers. The rocky core ended up falling into Saturn.

S&T: GREGG DINDERMAN

Where Did the Rings Come From?

The nature and origin of Saturn's ring system has perplexed astronomers for four centuries. Galileo sketched them as "ears" on the planet in 1610, but two years later they vanished from view when Saturn passed through an equinox. "I do not know what to say in a case so surprising, so unlooked for, and so novel," wrote the exasperated observer.

In 1859 James Clerk Maxwell proposed that the rings could not be solid but must instead be composed of numerous small particles, all independently orbiting Saturn. Dynamicists now realize that the rings lie within what's termed the *Roche limit*, inside of which tidal stresses from Saturn would tear apart any large solid object. Past attempts to explain Saturn's rings either assumed that the planet formed encircled by a close-in disk that could not assemble into a single object, or that a large body wandered too close to Saturn early in the solar system's history and was ripped apart by tidal forces.

But two aspects of the Saturnian system put serious constraints on any would-be explanation for those magnificent bands. First, the ring particles (in the main rings, at least) consist almost entirely of water ice. It's hard to imagine primordial leftovers or a hapless moon with a pure-ice composition — most likely it would contain roughly equal amounts of ice and rock. In addition, over time the rings should have become increasingly contaminated with rock, metal, and carbon from meteoroid strikes. Calculations suggest the accumulated debris should account for roughly 10% of the rings' mass, but observations suggest that it's no more than about 1%.

Second, the rings' origin must somehow be tied to that of Saturn's moons. It's self-gravity wakes might be masking several times more.

Once again Cassini might provide an answer. Its prime four-year mission ended in 2008, and a two-year extension carried it through a Saturnian equinox in 2010. Figuring that another spacecraft might not be sent Saturn's way for decades to come, NASA managers gave a green light to keep Cassini going until the planet reaches its northern summer solstice in May 2017.

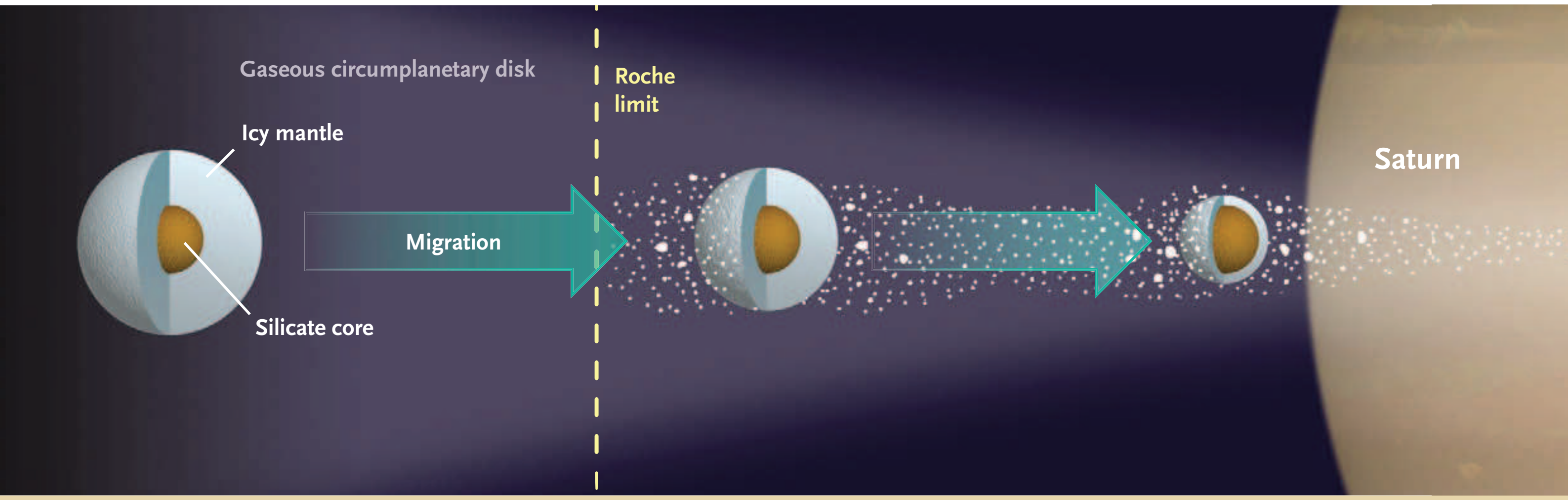
In the final 10 months of operation, mission controllers hope to reposition the spacecraft to perform a series of close-in maneuvers. First come 20 high-inclination orbits that pass just outside of the F ring. Then a close flyby of Titan will squeeze the periapse distance further, allowing Cassini to repeatedly dive through the clearing between the innermost D ring and Saturn's upper atmosphere that's only 3,000 km wide.

Careful tracking of the barnstorming spacecraft will not only reveal unprecedented details about Saturn's gravity field (and, from that, its internal structure), but also determine the rings' mass. Moreover, Cassini will map the inner magnetosphere and probe Saturn's ionosphere directly — and close-up images of the rings and planet should be breathtaking. "It's really exciting, and it's also fun," Burns muses. "The science is so different than what we've been able to do that it really changes the mission."

On September 15, 2017, one month shy of the 20th anniversary of its launch, the spacecraft will plunge into Saturn's atmosphere. But by then it will have amassed enough revelations to keep researchers busy for decades.

To see video animations of Saturn's rings in action, go to skypub.com/satrings.

*Senior contributing editor **J. Kelly Beatty** still gets a thrill whenever he looks at Saturn through a telescope.*



S&T: GREGG DINDERMAN

unlikely that the proto-Saturn nebula was big enough to form the massive moons Titan and Iapetus as far away as they are now from the planet, or that the mid-size moons near the rings could have ended up with such a wide range of densities (Tethys must be nearly pure ice, whereas neighboring Enceladus and Dione contain lots of rock).

So how can you pulverize a moon without adding lots of rocky rubble to the rings? The answer, says Robin Canup (Southwest Research Institute), is to take it apart very, very carefully. In late 2010, she proposed that a moon of roughly Titan's size — and which had segregated into a rocky core and icy exterior, as Titan has — started breaking up as it neared Saturn. But the Roche limit for disrupting a rocky body is much closer to the planet that the one for ice (because rock is denser). So while the moon's icy exterior was literally falling apart, the rocky core remained intact and eventually fell into Saturn.

All the chips-off-the-block left behind, orbiting close to the planet, would have been nearly pure ice. Moreover, there would have been a lot of them — totaling perhaps 20 billion billion tons, hundreds of times more mass than estimates for what the ring system holds now. "It would have been a vastly more massive initial ring," she admits. Later, lots of that matter would have migrated outward — beyond the Roche limit — where it became the building blocks for moons like Tethys.

Others have likewise posited that Saturn's mid-size moons are "children of the rings," but Erik Asphaug (Arizona State University) sees a glass half empty. "Canup's paper is very interesting, and I think those things happened," he says, "but I don't think you can make Dione and Rhea in that manner, let alone Iapetus."

Instead, Asphaug and Andreas Reufer (University of Bern, Switzerland) propose that Saturn was initially endowed with a set of big moons, like Jupiter's Galilean satellites, that collided and merged, ultimately forming Titan. In their computer simulations, these skirmishes liberate ice-rich spiral arms that later coalesce into Saturn's mid-size inner moons. A somewhat similar collisional scheme has been proposed by Yasuhito Sekine and Hidenori Genda (University of Tokyo, Japan), though in their view Titan was on the scene from the outset. ✦