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SEPTEMBER 2021

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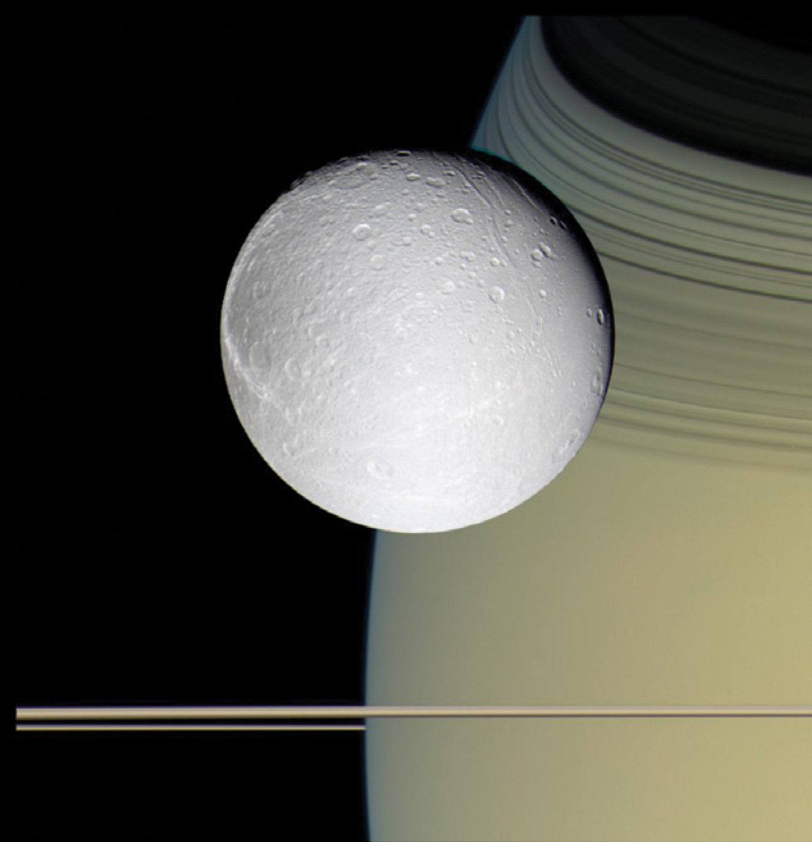
 by Monica Young

How Old Are Saturn's Moons?



A deceptively simple question has caused planetary scientists to rethink some basic physics.

▲ **MIDSIZE MOON** This view from NASA's Cassini juxtaposes icy Dione against the golden hues of Saturn in the distance. The horizontal stripes at the bottom are the rings; sunlight casts their shadows on the planet.

NASA / JPL-CALTECH / SPACE SCIENCE INSTITUTE

The Saturn system is beautiful, and beautifully weird. The magnificent rings inspire an "Oh wow!" when seen through even small telescopes, in part because they're so unexpected, almost as if the planet had sprouted ears. Every giant planet in the solar system has rings of some sort, but only Saturn's are so vast and so brilliant, composed almost solely of highly reflective water ice.

But the rings aren't the only unusual thing about this planet. The diversity of its extended family of satellites is unique among Saturn's giant brethren. Unlike Jupiter, with its four heavyweight moons and scores of small ones, Saturn has a third kind of companion: midsize moons, with diameters of 300 to 1,500 km (200 to 1,000 miles), or a tenth to almost half the span of our Moon.

Tucked between the lone heavyweight, Titan, and moonlets like ravioli-shaped Pan and Atlas, the midsize moons are varied mixes of rock and ice. Tethys, for example, is almost entirely made of ice — it would float if you could find a glass of water big enough. Meanwhile, Enceladus, although famous for its subsurface ocean, is more than half rock.

The riddles these moons pose promise insights into solar system history, if only scientists can solve them. While many of the gas giants' major moons probably formed in mini-solar systems around their planets billions of years ago, the midsize moons might have formed more recently, born from Saturn's rings. But attempting to answer the simple question "how old are they?" has led to a metaphorical tug-of-war among both observers and theorists. Amidst the back-and-forth, astronomers have realized they need to completely rethink some basic physics in the Saturn system.

What's New?

Most things in the solar system are ancient: 4.57 billion years old, give or take a few million. So it's unsurprising that astronomers thought the same of the Saturn system. But since the Voyagers passed by the giant planet in 1980 and 1981, astronomers have been debating that view. Measurements of the rings suggested they might actually be quite young, the recent remnants of a collision between moons or between a moon and some other trespassing object.

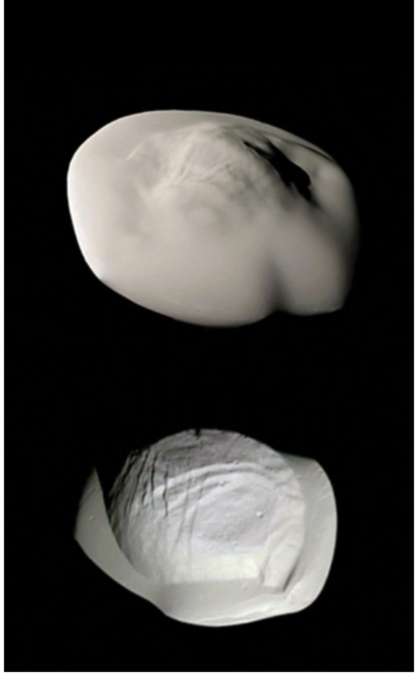
Two pieces of evidence support the notion of young rings. First, measurements by both the Voyagers and later by the Cassini spacecraft revealed that for all their vast expanse — the E ring spans almost 10 times Saturn's diameter — the rings are lean: They contain less than half the mass of Mimas, the smallest of the midsize moons. And the less massive the rings, the theory goes, the younger they must be, because the rings are slowly disappearing. Interactions between ring particles cause the rings to spread out over time. Any material that expands far enough from Saturn, past the so-called *Roche limit*, can clump up into moons. Meanwhile, the rings' inner edges are constantly losing material to Saturn's gravity; the Voyagers and Cassini even observed this *ring rain* as it fell.

Second, the rings are extremely reflective, made of 90–95% water ice. "They look like fresh snow," says Luke Dones (Southwest Research Institute). And just as snow dirties within a day in a city, thanks to the carbon-enriched smoke from cars and trucks, interplanetary meteoroids should darken the rings over time. Jupiter, Uranus, and Neptune have darker rings for this reason, yet Saturn's rings are still bright.

Since less massive rings would darken more quickly, some scientists have suggested that they must be quite young — less than 100 million years old. That's recent enough that the Triceratops and other dinosaurs of the Cretaceous Period would have been roaming Earth when the rings form. Yet the precipitating event — a moon-size collision — would have been so rare that many scientists remain uneasy with the idea of young rings. Even those in favor of a past collision acknowledge this, such as John Dubinsky (then at University of Toronto), who qualified such an event in a 2019 study as "perhaps unlikely, but not wildly so."

There's also a more general sense of discomfort with the young-ring scenario. Despite the circumstantial evidence, Dones counters, "there's no direct evidence that the rings are young." In fact, Dones worked with Aurélien Crida (Côte d'Azur University, France) and others to outline why the rings could be light, bright, and still be primordial — no moon smash necessary.

Take the mass, for example. Crida's team acknowledged that the spreading effect would cause the rings to lose material. But because more massive rings spread faster, they argue, the rings would have lost most of their material early on, eventually converging to a mass very like the one Cassini measured. So the rings' current leanness could be a sign not of youth but of age.



◀ **RAVIOLI MOONS** Atlas (above) and Pan (below) are two of the smaller moons. The ridges around their equators are made of particles they sweep up as they orbit within Saturn's rings.

It's even possible that the ring rain could preferentially "clean" the rings of organic material, leaving them looking shiny and new. Although the details of how this would work remain unclear, Cassini observations of the ring rain and of Saturn itself confirm that much of what is raining down consists of silicates and organics.

But Dones admits the debate is far from settled. "We've never really come up with a good reason why Saturn should be the planet that has a much more 'ginormous' ring system than the others," he says.

The unsettled age of the rings ties directly to the unsettled origin of the midsize moons, because the two structures are two sides of the same coin. Even as the rings' outer edges spawn new moons (including moonlets we've spotted in the act of forming), other moons donate material to the rings or even make them wholesale, in moon-destroying impacts. If the rings are young — and maybe even if they're not — then some of the midsize moons might be newcomers, too.

"Children of the Rings"

There's little doubt that Saturn's innermost moons are indeed "children of the rings," as first proposed by Sébastien Charnoz (then at Paris Diderot University). Observations bear this out. The ravioli shapes of Pan and Atlas likely come from the ice particles they've amassed as they orbit within and just

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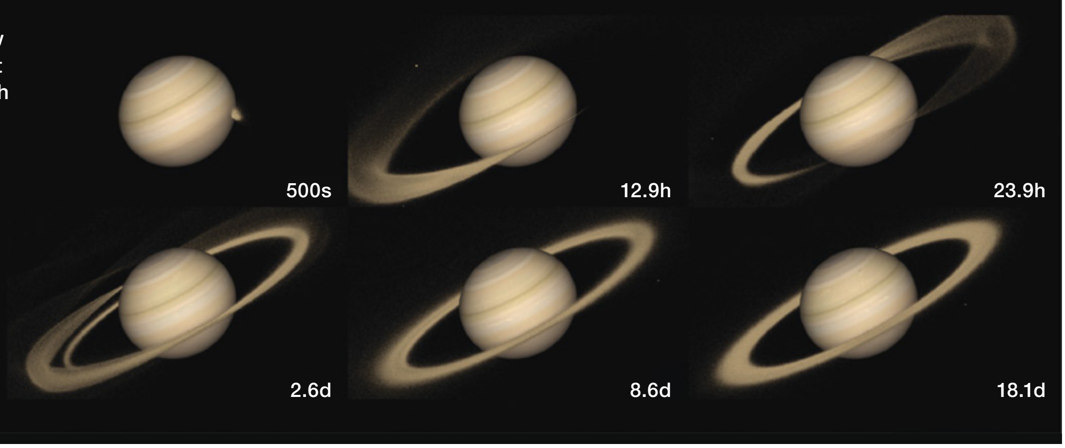


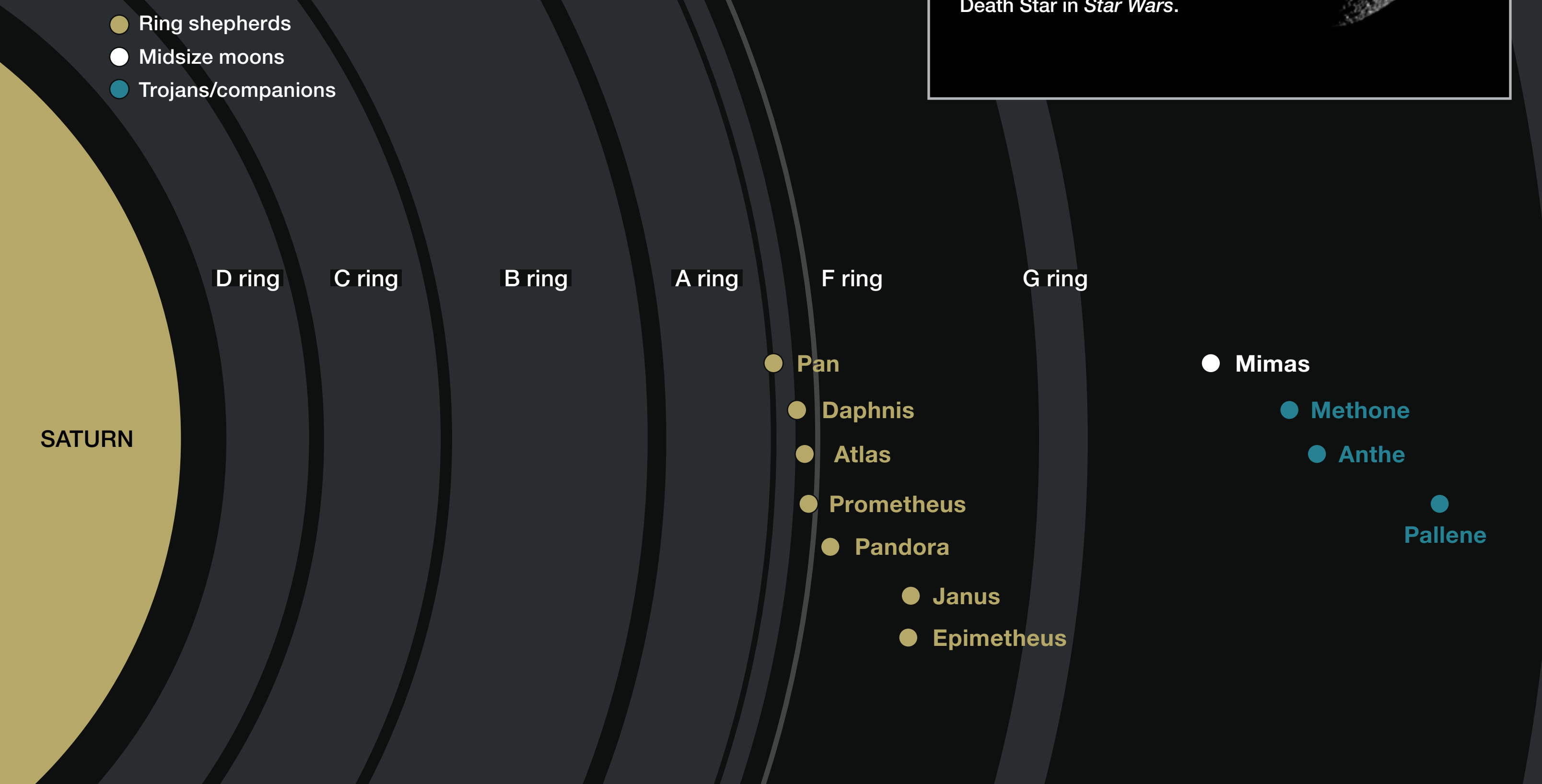
YOUNG RINGS These simulation frames show what would happen if a comet that happened to pass through the Saturn system smashed into a moon. The resulting debris would form wide, icy rings around Saturn, close to what we see now. However, the small likelihood of the smashup causes some scientists to doubt the scenario. (Watch the full animation at https://is.gd/newrings.)

PAN AND ATLAS: NASA / JPL / SPACE SCIENCE INSTITUTE; RING SIMULATION: JOHN DUBINSKI / *ICARUS* 2019

WELCOME TO THE FAMILY

This diagram shows Saturn's rings (labeled in the order of their discovery), ring-shepherding moons, and icy midsize moons. (Technically, Iapetus is also a midsize moon, but its orbit lies outside Titan's, so it doesn't interact with the others and may have a different origin.) The orbits are shown to scale, but the moons' sizes are not. Moons smaller than a kilometer across are omitted.

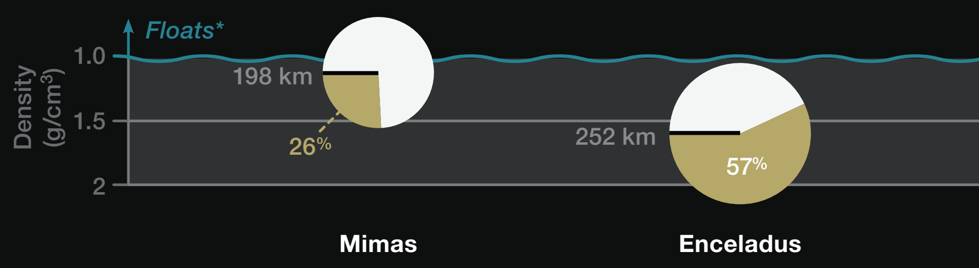
- Ring shepherds
- Midsize moons
- Trojans/companions



MIMAS This moon came to light as a dot in the telescope of William Herschel in 1789, long before the Voyagers and Cassini obtained closer views. Cassini's photo features the eponymous Herschel Crater that gives this geologically dead moon the appearance of the Death Star in *Star Wars*.

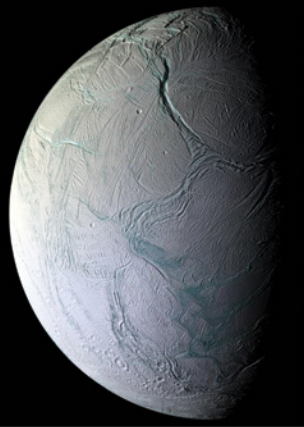
WOULD THEY FLOAT?

The five midsize moons inside Titan's orbit exhibit a diversity of densities (and therefore compositions) that has long defied explanation.



*Density of water is 1 g/cm³

ENCELADUS This Cassini image highlights the icy moon's *tiger stripes*, fractures from which the spacecraft observed water from an underground ocean geysering into space. The surface and activity make this moon strikingly different from Mimas, despite the two moons' similar sizes and orbits.



TETHYS Ithaca Chasma, which snakes to the right in this image, runs nearly three-quarters of the way around Tethys, the iciest of the midsize moons.

E ring

MOON SHAPES

Gravity rounds the shapes of more massive moons, while less massive ones remain lumpy. But origins matter, too: Moons forming in the rings collect icy material along their equators, giving them a distinct ravioli appearance.

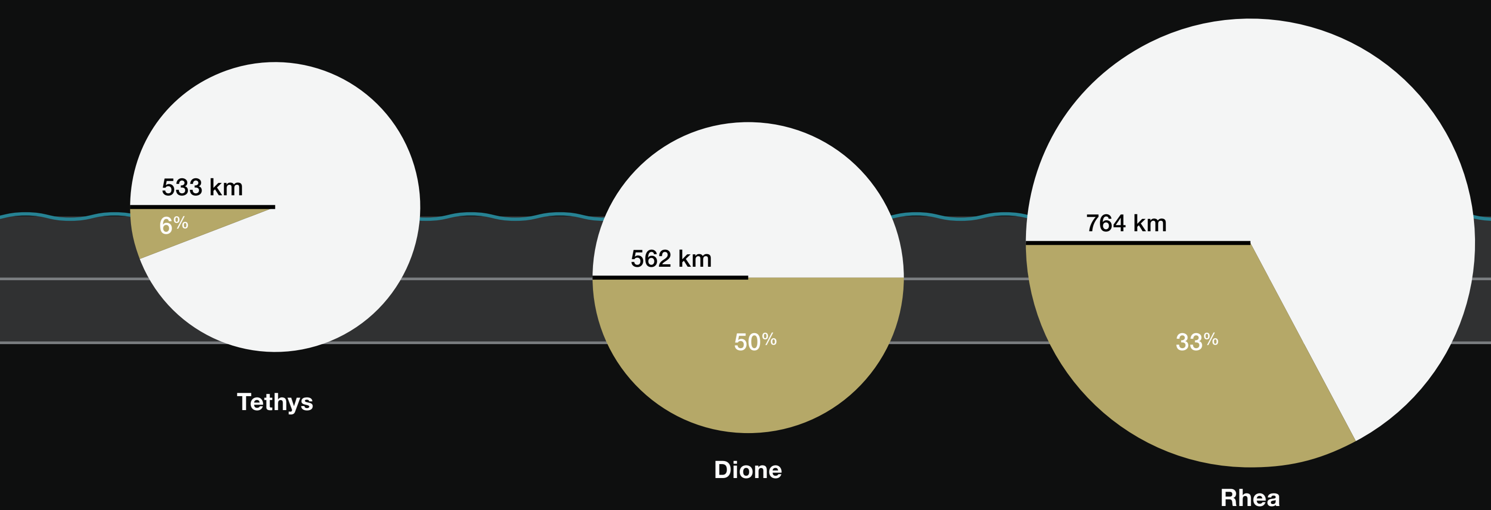
POTATO		RAVIOLI	ROUND
Prometheus	Anthe	Pan	Mimas
Pandora	Telesto	Daphnis	Enceladus
Janus	Calypso	Atlas	Tethys
Epimetheus	Helene		Dione
Methone	Polydeuces		Rhea
Pallene			

Enceladus

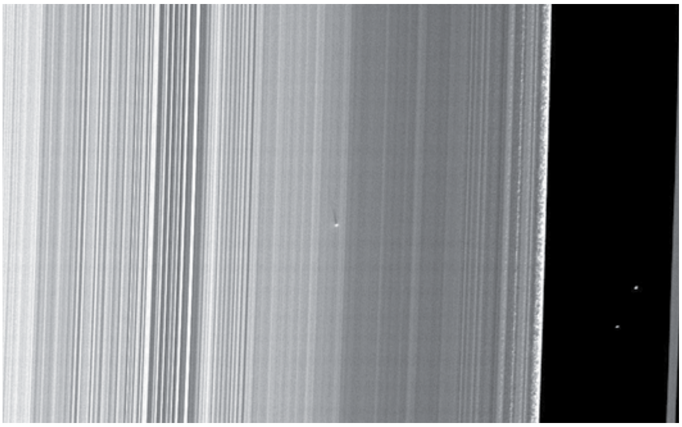
Tethys
Telesto
Calypso

Dione
Helene
Polydeuces

Rhea, Titan, Hyperion, Iapetus, and other moon families are farther out →



INFOGRAPHIC: TERRI DUBÉ / S&T; MIMAS, ENCELADUS, TETHYS, AND RINGS: NASA / JPL-CALTECH / SPACE SCIENCE INSTITUTE



▲ **MOONLET** Cassini caught a moon, designated S/2009 S1, in the process of forming within the B ring. The moonlet casts a shadow that stretches 36 kilometers (22 miles) across the rings, which suggests the object itself protrudes 150 meters above the ring plane.

(continued from page 15)

outside Saturn's A ring, respectively. Likewise, Prometheus and Pandora have been observed shepherding and frolicking with the faint and narrow F ring. One tiny world — a moonlet named S/2009 S1 — was even caught in the act of forming within the B ring.

But Saturn's midsize moons present more of a puzzle: Mimas, Enceladus, Tethys, Dione, and Rhea are surprisingly icy compared with Titan, but nowhere near as icy as the rings. In fact, the rocky fractions of their compositions range widely (between 6% and 57% silicates) in a way that doesn't seem to be tied to their distance from Saturn or even to their size.

Their geological activity is likewise diverse: Small Enceladus harbors a subsurface ocean that geysers into space (*S&T:* Aug. 2020, p. 32), while similarly sized Mimas is as geologically dead as the Death Star it resembles.

Small Enceladus harbors a subsurface ocean that geysers into space, while similarly sized Mimas is as geologically dead as the Death Star it resembles.

How astronomers explain this riddle of diversity depends very much on how old the moons are.

Scenario A: The Moons Are Young

There are two key observations that open the possibility of young midsize moons. First, there's their craters. Astronomers use craters as timekeepers, and they initially thought the moons were ancient because of all the craters that spot their surfaces (at least those not resurfaced by ice).

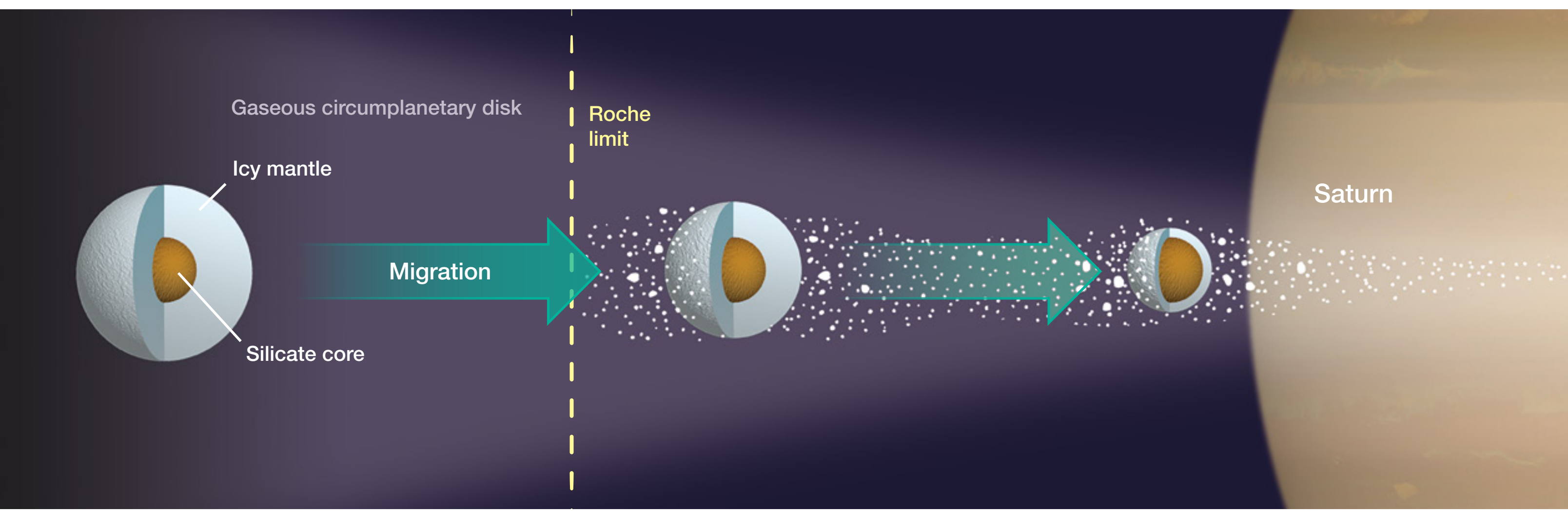
But more extensive analyses have revealed oddities that don't line up with the crater record on the Moon or elsewhere in the solar system. Many astronomers now think that most of the moons' craters could have come not from comets or asteroids circling the Sun but from objects within the Saturn system. If that's the case, then the moons could have been heavily cratered in a one-off event, throwing off the only reliable dating measurement that astronomers have.

"There's just no real way to understand how busy it has been around Saturn," explains Marc Neveu (University of Maryland). "The fact that there's a giant planet throws a wrench in things."

The second key observation was of the moons' orbits, which change over time due to tides. According to the classical idea of how tides work, each moon pulls on Saturn, deforming it ever so slightly into an oblate shape. (The Moon

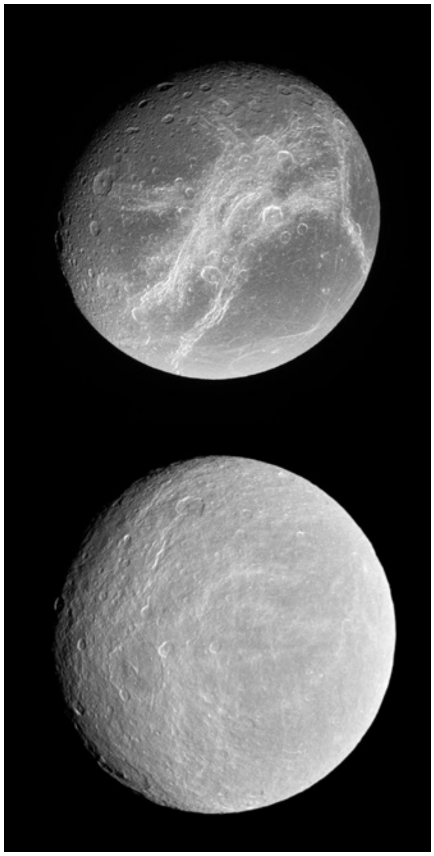
MOONLET: NASA / JPL / SPACE SCIENCE INSTITUTE; ICY MOON GRAPHIC: GREGG DINDERMAN / S&T

▼ **PRIMORDIAL RINGS** Under Robin Canup's proposal in 2010, a just-formed Titan-size moon would migrate inward toward Saturn due to interactions with the gaseous disk around the planet. Once the moon crossed the Roche limit, Saturn's tidal gravitational pull would remove the less-dense outer layer of ice, distributing it in a massive ring around the planet. The rocky core would ultimately plunge into Saturn.



does the same to Earth, though it's our planet's water that bulges.) The force of gravity directs the bulge toward the moon that's pulling it, but both the planet and the moon are in motion — and while Saturn spins every 10.7 hours, the moons take days to orbit once around. So gas must constantly reflow to reshape the planet as it spins, and friction hinders the bulge from ever catching up.

This never-ending tension torques Saturn, slowing its spin. It simultaneously transfers angular momentum to the moons, expanding their orbits. (The same happens on Earth, causing our day to lengthen by 23 microseconds every year and the Moon to back away by some 4 cm every year.)



◀ **DIONE** *Top:* The surface of this icy moon is both heavily cratered and fractured.

◀ **RHEA** *Bottom:* Saturn's second largest moon (not shown to scale here), Rhea is nevertheless only a quarter as wide as Titan. This view shows the cratered plains on its trailing hemisphere.

NASA / JPL / SPACE SCIENCE INSTITUTE (2)

Initially, when scientists assumed Saturn's moons were primordial, they figured that for Mimas to take 4.5 billion years to reach its current location, Saturn must dissipate only a little energy through tidal interactions.

Energy dissipates in complex and varied ways depending on the planet. Scientists lump these processes together under something called a *quality factor*, or Q for short. In simple terms, a higher Q means the planet's gas is slippery and can deform without much friction. A lower Q, on the other hand, indicates a body with "stickier" gas that experiences more friction and thus dissipates more energy.

For decades, scientists had assumed Saturn was fairly slippery, with a Q of at least 20,000. But that's not what Valéry Lainey (Paris Observatory) found. Studying observations of the moons' positions collected since 1886, including the extremely precise data collected during Cassini's 13-year run, Lainey and his colleagues realized that Saturn's Q factor is an order of magnitude lower than expected. In other words, the gas inside Saturn is surprisingly sticky and generates a lot of friction.

The theory also explains why Saturn has only one heavyweight moon: *It ate the others.*

Even more surprising was the implication for the midsize moons. It turns out their orbits are expanding more quickly than expected, especially Rhea's, which Lainey found was moving outward 10 times faster than previously thought. Run time backwards, and the midsize moons would fall into the planet a billion or so years ago.

Scenario B: Long Live the Moons

However, theorists have struggled to explain young midsize moons. Ancient moons, on the other hand, develop naturally in simulations that follow the evolution of Saturn's rings.

In 2010, Robin Canup (Southwest Research Institute) considered what would happen if Saturn had originally had more Titan-like moons, just as Jupiter has four Galilean heavyweights now. The multiple Titans, each with a rocky core surrounded by a thick layer of ice, would have orbited in the disk of dust and gas surrounding the newborn giant planet. Interactions with that disk would have dragged the massive moons inward over time, and one or more such moons might have ventured too close, inside the Roche limit. Since ice is less dense than rock, Saturn's tidal gravitational pull would have stripped off the moon's icy surface layers first. These would have settled into pure-ice rings much more massive than the ones we see today. The remaining rocky core would have plunged into Saturn.

"[This] is still the leading theory of how the rings formed," Dones says. The theory also explains why Saturn has only one heavyweight moon: It ate the others.

Under Canup's proposal, the newly formed rings would in turn have spawned smaller moons off their outer edges while still in the early days of the solar system. That process, she contended, could have created Tethys and those midsize moons inside its orbit, but not the heftier and farther-out Dione and Rhea.

Charnoz and others modified and extended Canup's idea. If some rock chunks remained in the rings, then *all* of the midsize moons could long ago have spun off the rings' outer edge. The size of the rock-chunk cores would have varied greatly, thereby explaining the variety of compositions: Tethys, for example, might have formed almost solely from ice chunks where no rock was available.

Charnoz and his colleagues explicitly tie the moons' origin to the rings, which they estimate could have formed anytime between 2.5 and 4.5 billion years ago. Mimas, the innermost and smallest of the bunch, is the exception, forming up to 1.5 billion years after Rhea.

Other variations on the moons-from-leftovers theme come to a similar conclusion: The midsize moons seem to be old, if not necessarily primordial.

Mimas Come Lately

But recently, some theorists have gone a step in the other direction, suggesting that at least some of the moons are geological infants.

Matija Ćuk (SETI) and his colleagues modeled the system's evolution to look for resonances between the moons' orbits. What they found was that as the orbits of Dione and Tethys expanded away from Saturn following the moons' formation, they ought to have gone through a stable 3:2 resonance, in which Dione would have orbited Saturn three times for every two times Tethys went around. But that inevitable resonance never happened.

"Tethys and Dione should have gone through this resonance 100 million years ago or so," Ćuk says. That resonance would have tilted their orbits, he adds, and they're not tilted enough. Moreover, there's no evidence of a major impact or another significant event that could have knocked the moons out of resonance. As a result, there's a limit on how old these moons — and thus their compatriots — could be, a limit that happens to line up nicely with the age that had been proposed for the young rings: on the order of 100 million years.

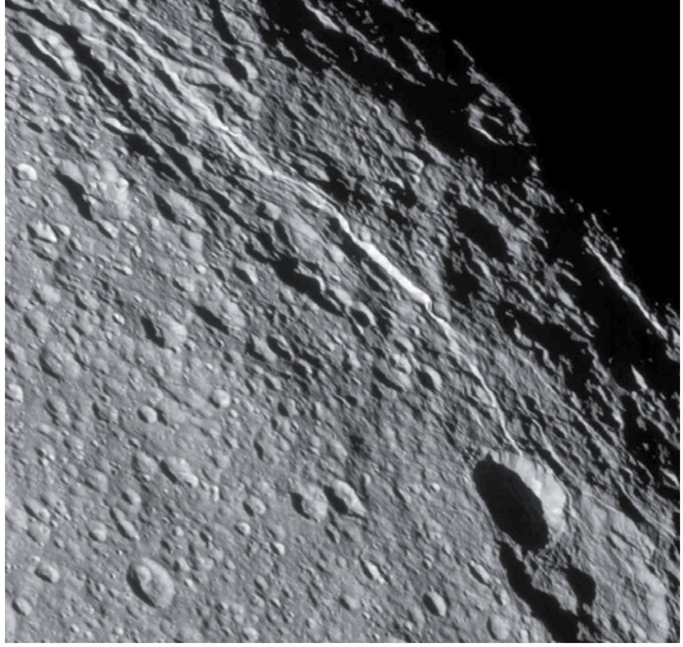
Perhaps not surprisingly, the finding was controversial. "I think it was provocative," Neveu says, "but it's another way to look at the issue."

Neveu put out his own proposal, based on numerical simulations of the midsize moons' orbits and interiors, that Mimas might be a child of the rings, born between 100 million and 1 billion years ago. But these same simulations only work if the other midsize moons are old.

A young age for at least Mimas might explain why it has no ocean. Enceladus supports its underground ocean by heat generated from tidal stresses. Mimas should experience similar tidal stresses, being roughly the same size and distance from Saturn. But if it's young, it wouldn't have enough residual heat to soften the ice to a point where tidal stresses could fully melt it.

A Sea Change

The flood of studies coming from observers and theorists alike in previous decades did little to settle the origins of the Saturnian system. Part of the trouble was that everyone



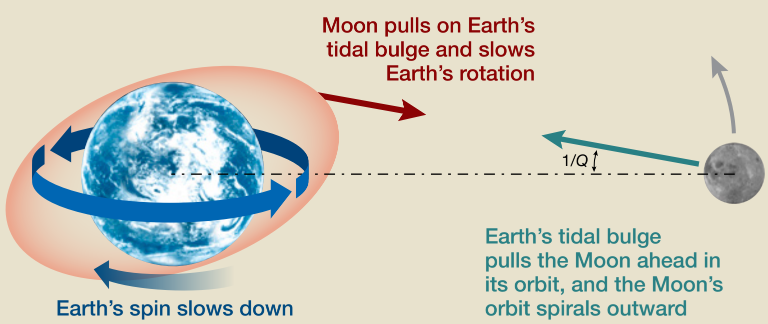
▲ **CRATER AGES** Heavily cratered terrain, such as on the surface of Rhea, suggests that the midsize moons are old. But that conclusion holds only if the impactors came from the solar system at large — if they originated within the Saturnian system, craters become less reliable indicators of age.

assumed we understand how a concept from freshman physics works on Saturn: tides.

Scientists rely on tides to explain everything from the behavior of moons' orbits to the heating of their internal oceans. But Lainey's research hinted that Saturn's interior behaves differently than expected, causing Rhea to back away more quickly than thought. Another researcher, Jim Fuller (Caltech), realized he might have the answer — not from planetary science, but from his studies of tides in close pairs of stars. That work had taught him a key lesson: When it comes to giant gaseous bodies, everything we thought we knew about tides is irrelevant.

"When you tidally distort a planet, it doesn't just distort into a nice egg or oval shape," Fuller explains. His simulations show that a gas planet actually oscillates, and it does so at many different frequencies at the same time. He compares the vibrations to an earthquake, but one with such low frequencies that any back-and-forth motion would be gradual, on timescales of hours. That motion likely comes in the form

CLASSICAL TIDES The gravitational pull of a moon causes a planet's water (or gas) to bulge in the shape of a rugby football. The angle between the tidal bulge and the moon is equivalent to 1/*Q*. If there were no friction inside the planet, the angle would be zero and *Q* would be infinity. But there is some friction, so the bulge can't instantaneously change its shape. Since the planet spins faster than the moon revolves, its bulge always points slightly ahead of the moon, pulling it along in its orbit. And as the moon speeds up, its orbit enlarges. The moon in turn pulls on the bulge, slowing the planet's rotation.



CRATERS ON RHEA: NASA / JPL-CALTECH / SPACE SCIENCE INSTITUTE; TIDES DIAGRAM: GREGG DINDERMAN / S&T

of waves traveling through the planet's gaseous interior.

As the moons orbit the pulsating planet, their orbital periods by chance might resonate with the frequencies of some of those pulsations. When that happens, the resonance amps up the volume. "It's like the moon is pushing on Saturn just at the natural frequency of the note it wants to play, so it makes the planet play a very loud note," Fuller says.

Once a moon's orbit hits the resonant frequency of the oscillations inside the planet, it will suddenly find itself migrating outward much faster, like a surfer catching a wave. The moon rides that wave, its orbit and Saturn's interior evolving in lockstep until the wave eventually breaks.

There are two related implications to come out of this *resonance locking*. First, just because a moon is migrating out quickly now doesn't mean it always has been — the dissipation of tidal energy isn't constant over time.

Second, the friction that tides generate still depends on distance — but in the opposite way than previously thought. While classical theory would tell you that farther moons should migrate outward more slowly, resonance locking instead suggests that farther moons migrate outward *faster*. In terms of an individual moon, that suggests its rate of migration was slow to begin with, but it sped up once it caught the resonant wave.

The expected difference in a moon's behavior depending on its distance from Saturn became a test, one that resonance locking passed with flying colors.

"One of the predictions of our paper was that Titan might be migrating out much faster than people expected," Fuller says. And that's exactly what Lainey found. "In fact, [Lainey] said he'd already seen it, but he didn't believe the results until he looked at the predictions," Fuller adds.

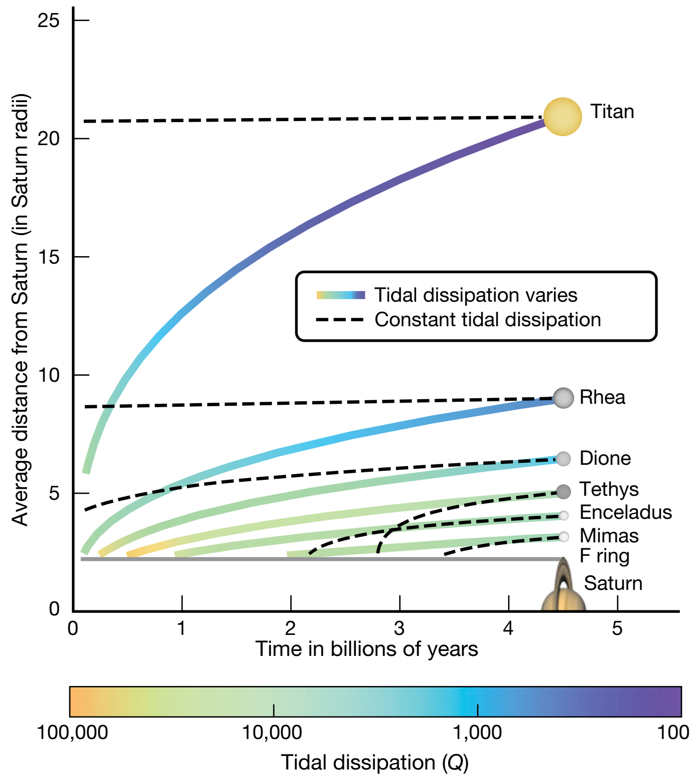
In 2020, Lainey and collaborators reported in *Nature Astronomy* that Titan was receding from Saturn at a surprising rate of 11 cm per year — 100 times faster than previously thought. Another team, including Neveu, is now looking to confirm that result independently.

The new understanding of tides caused the scientists involved to re-evaluate the midsize moons' origins: While their fast migration rates had pointed to young ages, now they only mean the moons are migrating fast today — the past is a different story. Likewise, theorists can no longer use predicted moon-moon resonances to date the moons, unless those simulations also take into account the effect of varying tides on orbital matchups.

But does that mean all of the moons really are ancient? "I don't think it provides a definitive answer either way," Fuller muses, "but it allows them to be older than people have previously assumed."

The Way Forward

While the new understanding of tides has completely changed the study of the Saturnian system — and even rendered some previous studies obsolete — it hasn't settled the debate. If anything, there's only more to consider now.



▲ **CHANGING TIDES** This plot shows how the evolving "stickiness" of gas within Saturn affects the orbits of its moons. Many of the midsize moons are migrating outward fast enough right now that, if time were rewound, those moons would fall within the rings not that long ago. But that's only true if Saturn's tides always dissipated the same amount of energy. If tidal dissipation evolves with time, then migration rates might have been slower in the past, and the moons could be much older.

GREGG DINDERMAN / S&T; SOURCE: LAINEY ET AL. / *NATURE ASTRONOMY* 2020

Young moons still have adamant advocates. Pointing to the observations of Titan's migration, Ćuk says, "Every time you add motion to the system, it makes old moons harder to have." Neveu also notes that changing tides could make collisions between moons more likely. And even Fuller's calculations show that some moons might yet be young.

Putting his idea into detailed numerical simulations will be difficult, Fuller says, because no one really understands Saturn's interior or how it has changed over time.

But there are ways to chip away at the problem. Several groups still work with the scads of exquisite data that Cassini returned during its years at Saturn. Fuller, for example, is using those data to turn the rings into a kind of seismometer to probe the planet's interior. Others continue to examine (and re-examine) the moons' migration.

Meanwhile, theorists are trying to find ways to incorporate the new physics into their simulations — it's an unexpected wildcard that has changed the game. But while this beautifully weird system may be keeping its cards close, that doesn't mean we'll stop playing.

■ News Editor **MONICA YOUNG**, award-winning science journalist, is on a first-name basis with Saturn's eclectic moons.