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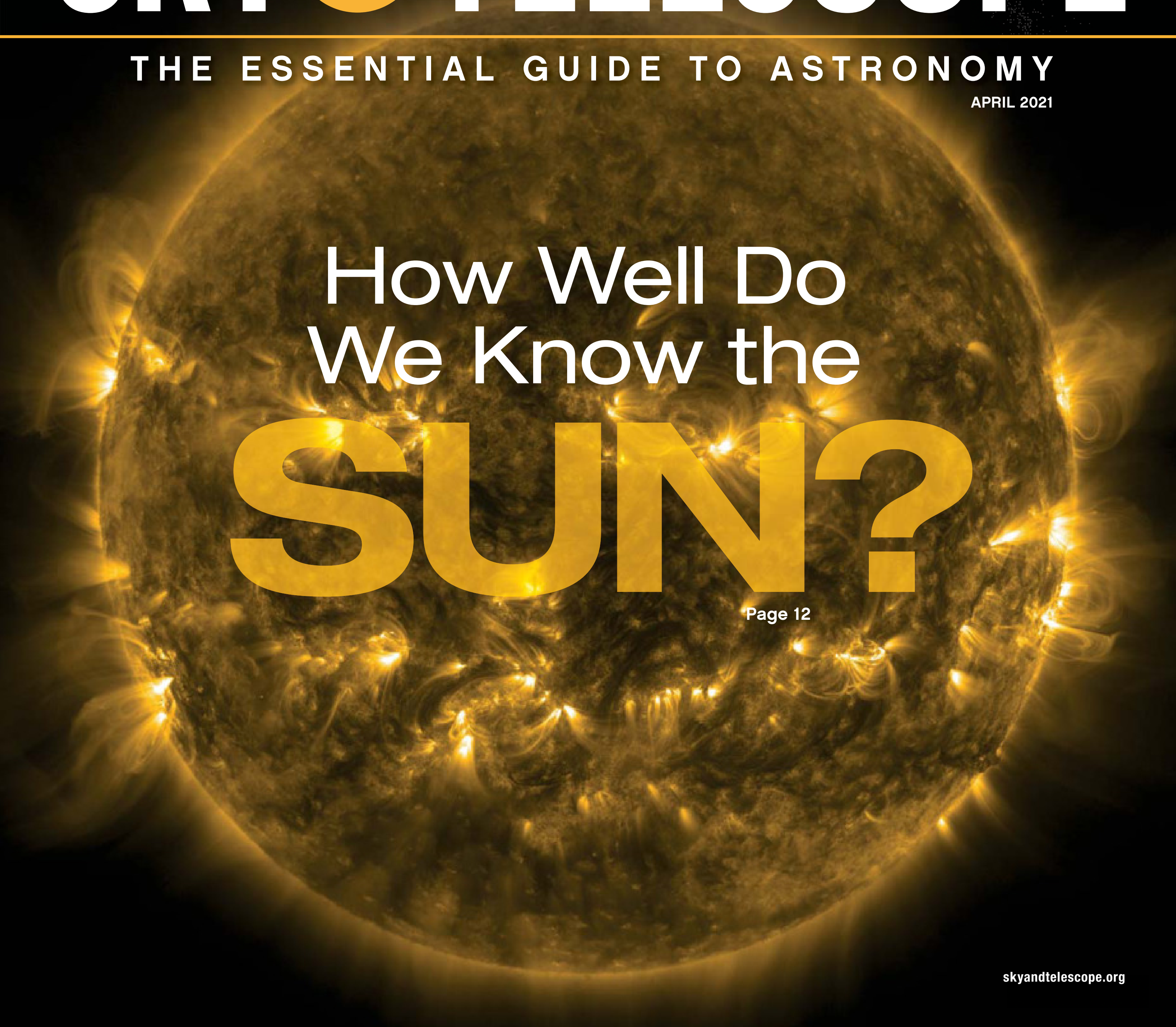
# SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

APRIL 2021



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# The Mys of the M

Planetary scientists may soon discover how the Red Planet acquired its two potato-shaped companions.

Phobos — the innermost of Mars's two moons — will provide a beautiful show to anyone lucky enough to be watching in 20 to 40 million years. The small satellite is losing altitude with each orbit, slowly inching towards Mars. But long before it crashes into the surface, tidal forces will shred it to tiny pieces. Its surface already shows signs of its imminent collapse: long faults that run for many kilometers across the landscape, which is covered by a thick layer of powdered rock. When Phobos finally fails, it will turn to rubble — dust, pebbles, and boulders that will stretch out like a spaghetti noodle in a ring around Mars.

The cataclysmic finale of Phobos doesn't puzzle scientists nearly as much as the mystery of its formation. American astronomer Asaph Hall discovered the Martian moons, Phobos and Deimos, in August 1877 and named them after two sons of Ares, the god of war in Greek mythology. Many theories aim to explain their origin, but none of them fully grasps how these small, battered bodies could end up orbiting Mars in perfectly circular orbits, right on the equatorial plane. Are these captured asteroids? Are they as old as Mars? Did they emerge after a giant impact like the one that formed Earth's Moon? Recent research unveils a complex picture.

A robotic mission to the Martian moons could answer these questions, but technical mishaps have doomed the three attempts made so far by the Soviet and later Russian space programs. Now is the turn for the Japan Aerospace Exploration Agency (JAXA), which in 2024 will send a spacecraft to visit both moons and return samples from Phobos to Earth. Its success will reveal how the Martian moons formed, shed light into the chaotic history of the solar system, and — for the first time — bring samples from the Martian system to our planet.

## A Strange Pair of Moons

Phobos and Deimos are the first non-spherical solar system

◀ **PHOBOS OVER MARS** The Mars Express orbiter caught this image of Phobos over Mars's limb on March 26, 2010. (The waviness in the background is due to the camera's line-scanning method.)

ESA / DLR / G. NEUKUM (FU BERLIN)

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# artian Moons

bodies ever explored up close. When Mariner 9 beamed back the first clear images of the moons, scientists could finally see their lumpy and asymmetric bodies: Their gravity is too weak to mold them into a spherical shape. Compared to Earth's Moon or the Galilean satellites of Jupiter, they are mere boulders. Deimos is just 12 kilometers (7.5 miles) in diameter and lies 23,460 kilometers from Mars. Potato-shaped Phobos averages 22 kilometers in diameter and orbits some 9,380 kilometers from the planet's center — less than 6,000 km above the surface, making it the closest moon to its planet in the solar system. For comparison, our Moon is 3,480 kilometers wide and orbits 384,400 kilometers from Earth. Deimos and Phobos's tight orbits, small sizes, and dark surfaces likely delayed their discovery.

The moons travel in the same direction that Mars spins. Deimos completes an orbit in 30 hours, a bit longer than the planet's 24.6-hour rotation, so as seen from the Martian surface it slowly rises in the east and eventually sets in the west. But Phobos takes just 7.65 hours to complete an orbit — much faster than the planet's spin rate — so it rises in the west and sets in the east, zipping across the sky three times every Martian day.

Both moons are rocky and pockmarked by myriad craters. Phobos, Mariner found, sports a massive, 10-kilometer-wide crater named Stickney on one end. Stickney was the maiden name of Hall's wife, who had been trained as a mathematician and encouraged him to persevere in the search for Martian moons.

Phobos's surface is marred by a series of linear, trench-like grooves, shallow and long fractures that in some cases run for tens of kilometers. Many grooves seem to radiate from Stickney, leading scientists to think that they were formed either by the impact itself or by rolling boulders ejected during the event. While this might be the case for some of the grooves, researchers have recently spotted a population of cracks whose geometry isn't related to Stickney. Instead, they seem to be caused by the gravitational pull between Mars and Phobos, which might be warping Phobos's interior and producing stress faults on the surface.

These faults provide clues about the satellite's internal structure and composition. Phobos is covered by a layer of regolith at least five meters deep — the dusty residue accumulated after millions of years of asteroid impacts. If Phobos were solid all the way through, the tidal stress would be too

**DEIMOS (enhanced color)**

Approx. Size: 15 × 12 × 10 km

Rotation period: 1.26 days

Density (water is 1): 1.75 g/cm³

Average distance from Mars: 23,460 km

**PHOBOS (enhanced color)**

Approx. Size: 26 × 22 × 18 km

Rotation period: 0.319 day

Density (water is 1): 1.90 g/cm³

Average distance from Mars: 9,380 km

NASA / JPL-CALTECH / UNIVERSITY OF ARIZONA (2) weak to cause fractures. Instead, observations show that internally it resembles a rubble pile, a collection of jumbled materials of varied sizes. Such interiors deform easily under pressure, stressing the mildly cohesive regolith layer and eventually breaking it.

Deimos, on the other hand, looks like a quieter place. It has the overall lumpy and irregular shape of Phobos and is equally covered in craters, but they appear more subdued, suggesting that the regolith layer might be thicker than on its neighbor. It lacks any massive impact feature or signs of structural collapse, but it has two large craters named Swift and Voltaire, two authors that anticipated the existence of Martian moons in their literary work.

## Not Asteroids

The origin of Phobos and Deimos is still unclear. More than four decades after the Mariner and Viking probes returned images and spectrographic observations of the moons, scientists are still considering two possibilities.

The spacecraft revealed that the moons are among the darkest known solar system objects. They didn't show spectral signatures that could give away any minerals on their surfaces. They also appeared to be porous, either hollow or filled with water. These characteristics, along with their battered, irregular shapes, led scientists to believe that they could be captured asteroids.

"Those sorts of spectra are usually found in primitive meteorites, the kind of things we think Bennu and Ryugu are made of," says Andrew Rivkin (Johns Hopkins University Applied Physics Laboratory), who has thoroughly studied the moons' spectra.

However, their looks could also correspond to basaltic rocks that have been sitting out in space, bombarded by micrometeorites over time. That would imply a radically different origin, likely a giant impact that blasted Martian material into space, Rivkin explains.

"For quite some time we thought that it was more likely that they were like the carbonaceous-chondrite meteorites, primitive bodies that would have been captured by Mars," Rivkin says. However, "the people who study the orbits, the dynamicists, have always said there's no way you can capture these into an orbit like Phobos's."

Captured asteroids should wind up in highly elliptical orbits and randomly oriented around the planet's spin axis. Instead, Phobos and Deimos describe neatly circular orbits, right above the equator. "Unless [an asteroid] has engines and fires them exactly in the right way, you are not gonna get that," says Matija Ćuk (SETI Institute), an expert in orbital dynamics. "It just looks much less likely than kicking stuff out in an impact."

But the giant-impact theory wasn't seriously considered for the Martian moons until very recently, even after being widely accepted for our own Moon decades ago.

"If you look at the terrestrial planets, you have a big moon only around Earth, you don't have any moons around Mercury, neither around Venus, and you have two very small moons around Mars," says Pascal Rosenblatt (University of Nantes, France). "No one was convinced of the idea that [giant impacts] could be a universal process to form moons around terrestrial planets."

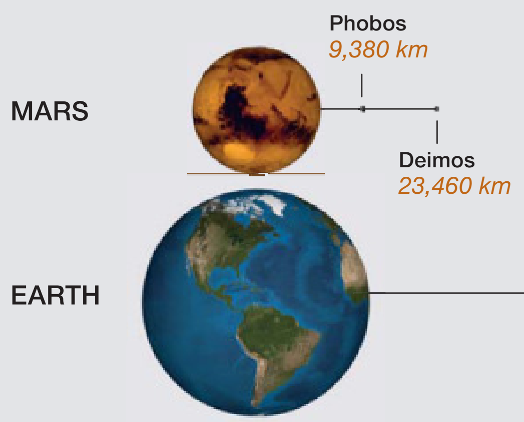
While still on the table, the orbital evidence paints a bleak picture for the capture scenario. "It's a best-of-seven series, and I think the impact theory is up three games to one," Rivkin says. "It's not quite done, but it's looking like it's going to be the impact theory to me."

## Same Ingredients, Different Results

But scientists are puzzled. How could the same process that made Earth's Moon also create two satellites so different from our own?

In 2016, Rosenblatt, along with Sébastien Charnoz (Paris Institute of Earth Physics, France) and other colleagues, published the result of a series of computer simulations that, for the first time, showed that Phobos and Deimos could have formed from a giant impact. Rosenblatt got his inspiration after the European Space Agency's Mars Express orbiter approached Phobos in March 2010, confirming that the small moon is barely twice as dense as water — roughly two grams

PHOBOS: ESA / DLR / G. NEUKUM (FU BERLIN); DEIMOS: NASA / JPL-CALTECH / UNIV. OF ARIZONA; EARTH: RETO STÖCKLI / NASA EARTH OBSERVATORY; MARS: ASU / NASA; MOON: NASA / GSFC / ARIZONA STATE UNIV.; INFOGRAPHIC: TERRI DUBÉ / S&T




**MARTIAN CLOSE-UP** Deimos orbits 15 times closer to Mars than the Moon does to Earth. Phobos is even closer: Its orbit is 40 times tighter than the Moon's. Phobos and Deimos's sizes are exaggerated here for visibility.

per cubic centimeter. This led Rosenblatt to think that Phobos might have accreted in orbit from chunks of rock blasted to space by a powerful impact. These irregular rocks would have left empty voids between themselves as they stuck together, explaining the moon's low density.

A giant-impact origin instantly solves the main problem of the capture scenario: The material kicked into orbit by the impact quickly forms a ring around the equator, where the moons coalesce shortly after.

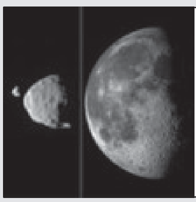
"This is a good trick," Rosenblatt says. "But you also have to explain the current distance of the moons to Mars and their masses."

The orbits have changed over time due to tidal dissipation. As the moons raise tides on Mars and vice-versa, they transfer momentum between them. Phobos is below the *synchronous orbit*, where objects complete a loop around the planet in the same amount of time that the planet takes to rotate. The tide that Phobos raises in the Martian ground thus lags behind the moon, slowing it down. As a result, Phobos loses velocity and altitude. Deimos is above the synchronous orbit, traveling slower than the planet's surface. In this case, the tide gets ahead of the moon, dragging it forward. This boosts the moon's orbit higher. This is why Deimos is slowly drifting away from Mars — as our Moon does from Earth.

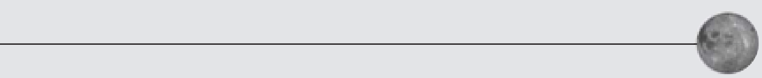
"We have a very stringent constraint just there: We have to form a Phobos more massive than Deimos, and the Phobos has to form below the synchronous orbit and the Deimos above it," Rosenblatt explains.

Not knowing how large the protoplanet that hit Mars might have been, Rosenblatt and his colleagues looked at Borealis Basin, the lowlands that cover most of the planet's northern hemisphere. Borealis is thought to have formed after a giant impactor 2,000 kilometers in diameter — one-third the size of Mars — hit the young Red Planet about 4.5 billion years ago. Such an impact could have blasted 100 quadrillion tons of rock into the Martian orbit, or 10,000 times the mass of Phobos and Deimos combined.

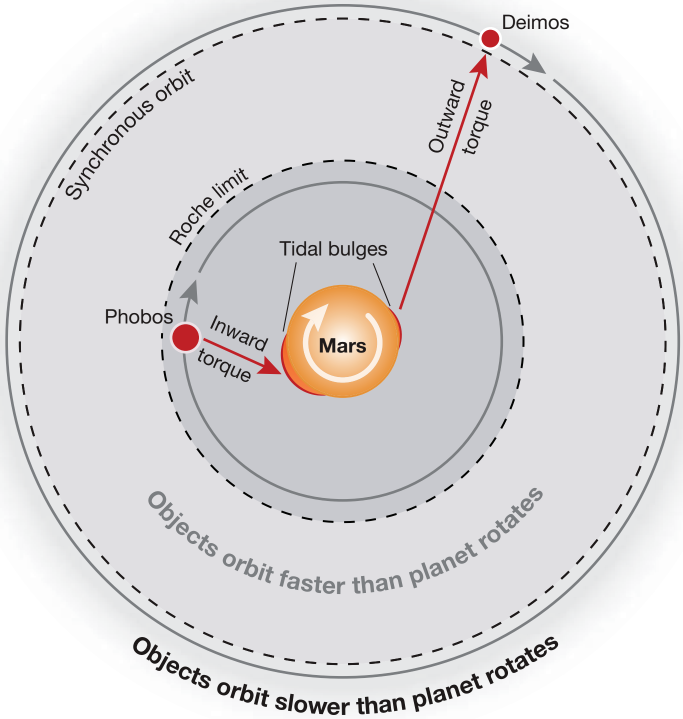
After such an impact, the simulations show, the orbiting material assembles into a disk around the equator in little



◀ **FROM THE GROUND** This composite shows the Martian and terrestrial moons at the sizes they'd appear when seen from the surfaces of their respective planets. Hold the page at arm's length for the approximate effect.




SIZE COMPARISON: NASA / JPL-CALTECH / MALIN SPACE SCIENCE SYSTEMS / TEXAS A&M UNIV; MOON: NASA; ORBITS: GREGG DINDERMAN / *S&T*, SOURCE: E. ASPHAUG / *NATURE GEOSCIENCE* 2016




▲ **SATELLITE ORBITS** Deimos orbits just beyond Mars's *synchronous orbit*, the distance at which a satellite's orbital period equals the planet's rotation rate. Inside the synchronous orbit, tides will force massive satellites to spiral in toward Mars; outside it, they'll push the satellite away. Within the Roche limit, Mars's tidal influence will tear the satellite apart.

more than a day. Most of the material stays below the *Roche limit*, an invisible boundary where the tidal influence of the planet prevents the formation of moons. Random collisions between particles expand the disk's outer edge beyond the Roche limit, where a large moon 1,000 times more massive than Phobos forms.

As the disk continues to expand, it pushes this large moon outwards, and its gravitational tug produces orbital resonances that "shepherd" the material above it into stable zones where the debris can concentrate. In Rosenblatt´s simulations, Phobos and Deimos form in these zones.

All the moons, including some smaller ones spawned at the Roche limit after the large moon moves out, continue to migrate outwards until the disk runs out of material. Without a driver for outward migration, the moons begin to fall back into the planet, dragged by tides. At this point, only Deimos has been pushed beyond the synchronous orbit, starting its slow outward drift to its current location. All the other moons either crash into Mars or disintegrate in orbit, torn apart by tides.

Phobos could be the last straggler. Formed closer to the synchronous orbit than its siblings, it has made it to our days, although its death date is nigh: It has already crossed the Roche limit, and its cracked surface forecasts its imminent destruction.

## PEEKABOO MOONS

Because they orbit so close to Mars, Phobos and Deimos aren't visible from all parts of the planet's surface. An observer poleward of about 80° latitude couldn't see either of them. Deimos would be visible equatorward of that, but you'd have to be lower than 70° north or south before you'd see Phobos. If that were true on Earth, people in the northern half of Greenland or nearly anywhere in Antarctica wouldn't see the Moon.

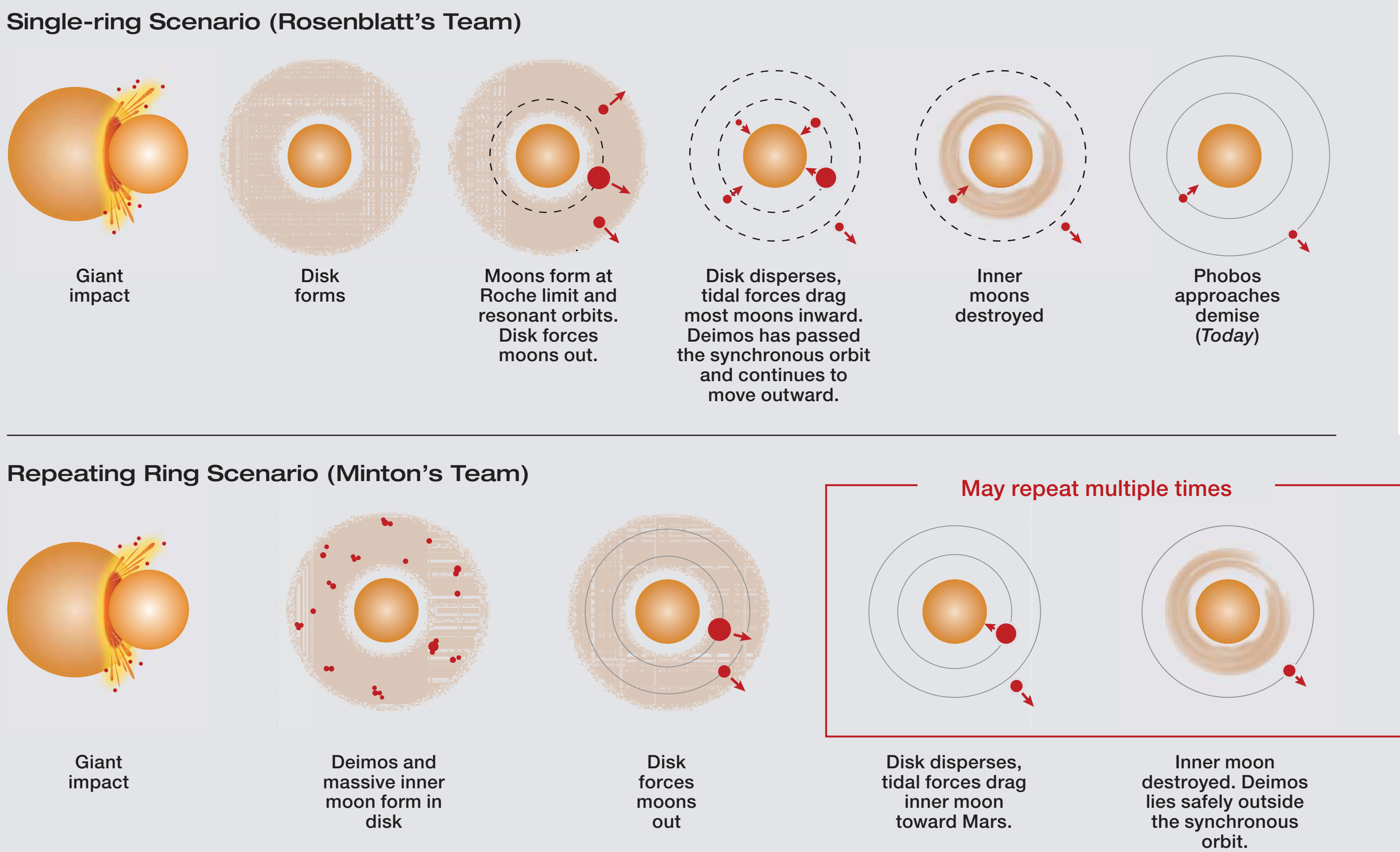
## Ring, Moon, Rinse, Repeat

After seeing the work by Rosenblatt and Charnoz, David Minton (Purdue University) decided to look into the problem himself. He was intrigued by the fate of Phobos and how it could survive for billions of years after its siblings disappeared. "If Phobos is very ancient and really originated in this giant impact early in the solar system's history, we're really lucky to be seeing it near the end of its life," Minton says. Then, he wondered: Could Mars have had more than one of these Phobos-like moons?

Minton found a clue in a 2015 study that, after gauging the structural strength of Phobos, predicted that the moon will collapse in 20 to 40 million years. When that happens, the study found, Phobos will turn into rubble and form a ring around Mars, not unlike Saturn's rings. This led Minton to think that maybe the moons that form below the synchronous orbit of Mars are cyclically destroyed and turned into rings, only to have smaller moons accrete from their remains.

Along with Andrew Hesselbrock, his graduate student at the time, he created new simulations in which a large impactor produces a heavy disk where Deimos and an inner moon 1,000 times more massive than Phobos form. The large moon migrates outwards while the disk is present, but then falls back into the planet until it's torn apart by tidal forces. The shredded moon forms a ring of debris around Mars, which again spreads outwards to form new moons above the Roche

ROSENBLATT'S SCENARIO: GREGG DINDERMAN / *S&T*; MINTON'S RING-AND-REPEAT SCENARIO: GREGG DINDERMAN / *S&T*, SOURCE: E. TASKER / JAXA



limit. “Then you rinse and repeat,” Minton says.

With every cycle, about one-fifth of the mass in the ring clumps together to form new moons, while the rest falls into Mars, resulting in smaller moons with every generation. Phobos might have been destroyed and rebuilt six or seven times, depending on how massive the post-impact disk was.

If Minton is right, Deimos ought to be billions of years old and Phobos just a few hundred million — just as old as the last ring-moon cycle. This is something that a robotic mission to the moons could elucidate.

In the meantime, the ring-moon theory has found some backing in an often-overlooked characteristic of the Martian system. The orbit of Deimos is off by two degrees from the equatorial plane of Mars. “Two degrees doesn’t sound like much if you’re driving, but actually it’s quite a bit for the very precise orbits of inner moons,” says Ćuk, who has partnered with Minton to test these ideas.

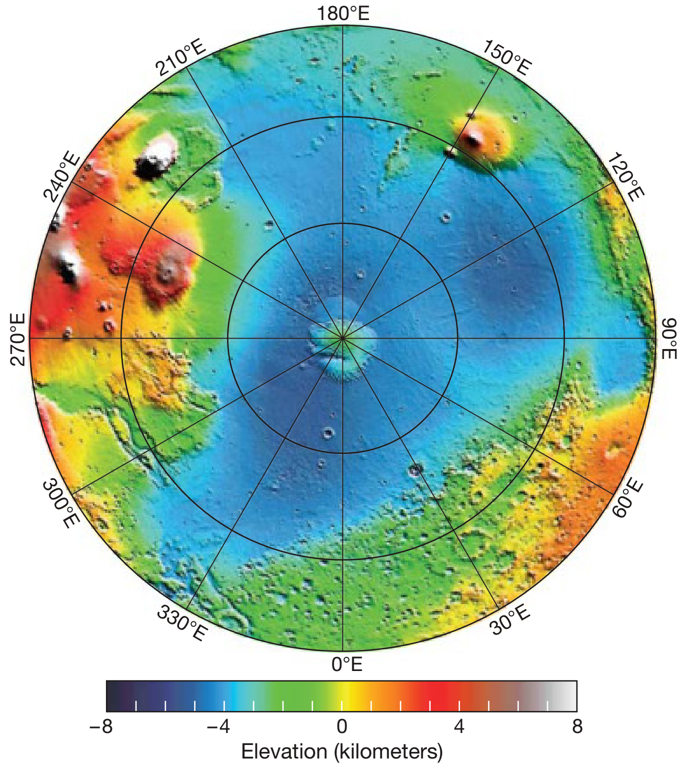
Ćuk found that an inner moon migrating outwards and caught in a 3:1 resonance with Deimos — orbiting Mars three times for each loop by the tiny moon — could have tilted its orbit while keeping it circular.

This kind of resonance works like a swing: A small push at the right time boosts the orbit of the outer body. Ćuk thinks that the resonance shoved Deimos to a slightly larger orbit at the cost of the orbit becoming tilted. “There’s no free lunch: Something, somewhere, has to be compensated for this increase of the size of the orbit,” Ćuk says. “The fact that its orbit is round but out of plane tells you that it wasn’t a random process.”

He also rules out impacts or close encounters with other bodies. “If you had just kept giving it random kicks the orbit would stop being circular as it goes out of the plane.”

Once Deimos broke free from the resonance, the tilting stopped, revealing the mass of the lost moon like the fossilized footprint of a long-extinct creature. Ćuk’s calculations show that the mass matches Minton’s predictions for Phobos’s “grandparent,” a moon 20 times more massive than Phobos that existed 3 billion years ago.

NASA / JPL / GSFC

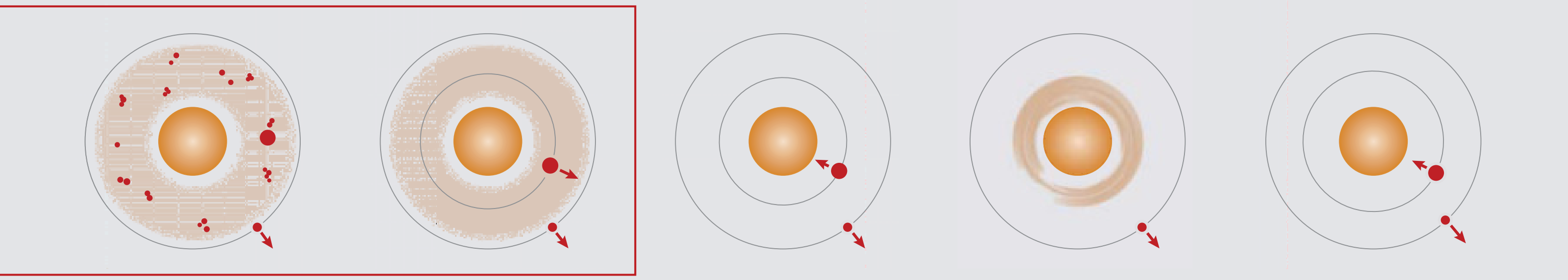



▲ **IMPACT SCAR?** Geologists suspect that the vast lowlands in Mars’s northern hemisphere (blue) are the vestiges of an ancient impact. Subsequent events obfuscated the basin, and today the stark topographic dichotomy is the only surface manifestation. This map is an equal-area projection of pole-to-equator topography.

“We’re looking for ways of testing this hypothesis and, like any good scientists, I’d be happy to see it challenged and whether or not it all hangs together,” Minton says. “But I’m more excited to see what we’ll learn when we actually study these objects really up close.”

## Fly Me to the Moons

To solve the riddle, scientists worldwide are looking forward



New, smaller inner moon forms.

Disk pushes inner moon out. During one of these cycles, the inner moon catches Deimos in a 3:1 resonance and changes Deimos’s orbital inclination.

Disk disperses, tidal forces drag inner moon toward Mars. Deimos continues to move outward with new orbital inclination.

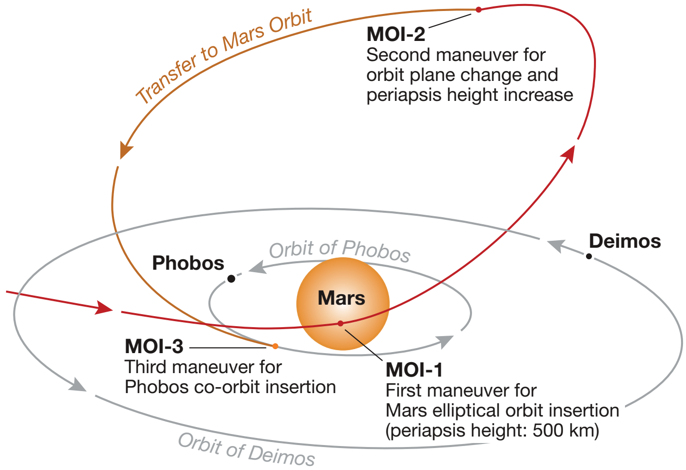
Inner moon destroyed.

Phobos forms from disk, now approaches demise. (*Today*) to Japan's Martian Moons Exploration (MMX) mission. Expected to launch in 2024, it will send a spacecraft to study both moons from orbit for about three years. It will also deliver a microwave-sized rover that will explore Phobos from the surface. Finally, the spacecraft itself will land on Phobos to retrieve samples and bring them to Earth.

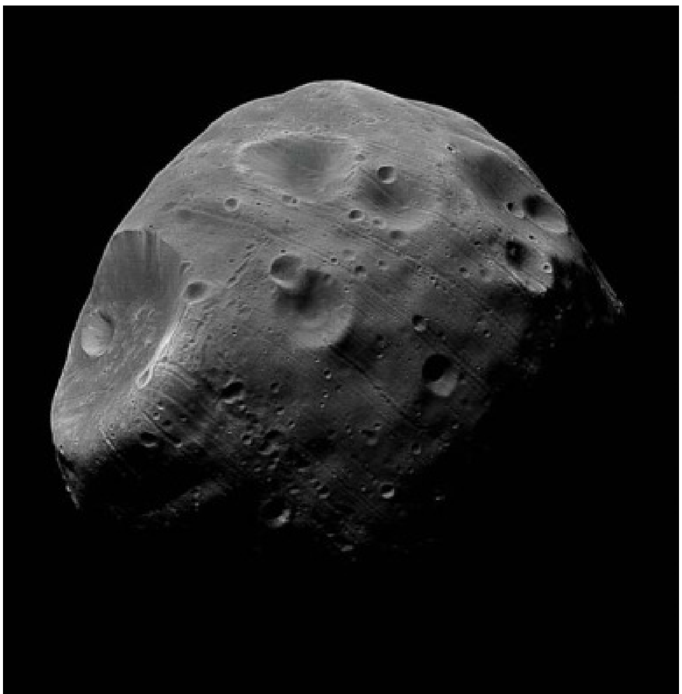
MMX aims to unravel the origin of the Martian moons and to investigate the evolution of the Martian system. "With these samples," Rosenblatt says, "we will be able to have a very reliable measurement of the age of Phobos, and we will see if David Minton is right or if I am right."

Or, the captured-asteroid scenario might still win out. Whatever the mission finds, MMX will provide invaluable insight into the evolution of Mars, our own planet, and the early solar system. If the impact scenario is correct, the moons should contain minerals from Mars from a time when it might have been habitable. "Comparing this satellite time capsule with present-day Mars would provide insight into how a habitable environment developed and then died," says Tomohiro Usui (JAXA), project scientist on the MMX team. Conversely, if the moons are captured asteroids, it means they originated elsewhere in the solar system. "This would make the moons examples of celestial delivery packages that were scattered between the outer and inner solar system, potentially delivering water and even primitive organics to the terrestrial worlds."

The highlight of the mission is the sample return. JAXA is building on its experience with the Hayabusa 1 and 2 spacecraft. While riddled with technical problems, the former managed to return some grains of material from near-Earth asteroid 25143 Itokawa. The follow-up mission, Hayabusa 2, had a smoother ride, successfully retrieving samples from asteroid Ryugu that safely dropped to Earth in December 2020 (see page 11).




▲ **PLANNED TRAJECTORY** Once Japan's MMX spacecraft enters the Mars system, it will execute a series of maneuvers to insert itself into a *quasistationary orbit* (QSO) around Phobos. A QSO is similar to a geostationary orbit, except that, instead of hovering over the same patch of surface, the satellite moves in a figure eight.



**POCKMARKED** The crater Stickney is the largest scar on Phobos, seen here from a distance of less than 200 km by the European Mars Express orbiter. Linear fractures also mar the moon.

Those who investigate the moons hope that MMX will deliver as much information about the Martian system as the Apollo program did for Earth and its Moon.

"Phobos and Deimos were kind of ignored for a long time, but they're the only other moons in the inner solar system," Minton says. "We've learned a lot about how our solar system formed by understanding how our Moon formed and what history it went through. So I think the existence of these two little moons of Mars is telling us something about the early solar system and how planets form."

The results will also enhance our understanding of a process that might occur time and again across the universe — and might be key to the evolution of life. "It's very important to understand if moons around terrestrial planets are commonplace, because our moon has played and still continues to play a very important role for the apparition and the maintaining of life," Rosenblatt says. "It has an impact on our future understanding and the exploration of the extraterrestrial planets."

But first and foremost, MMX will help solve a riddle that has puzzled astronomers for decades. "We're all really looking forward to the Japanese mission and keeping our fingers crossed," Rivkin says.

■ **JAVIER BARBUZANO** is a freelance science writer based in Spain. While researching and writing this feature, he welcomed his second daughter, Clara, into the world. He proposed several astronomy-related names for her, but his wife wouldn't budge.