PNAS INNER WORKINGS

An ambitious new mission seeks the origin of the moons of Mars

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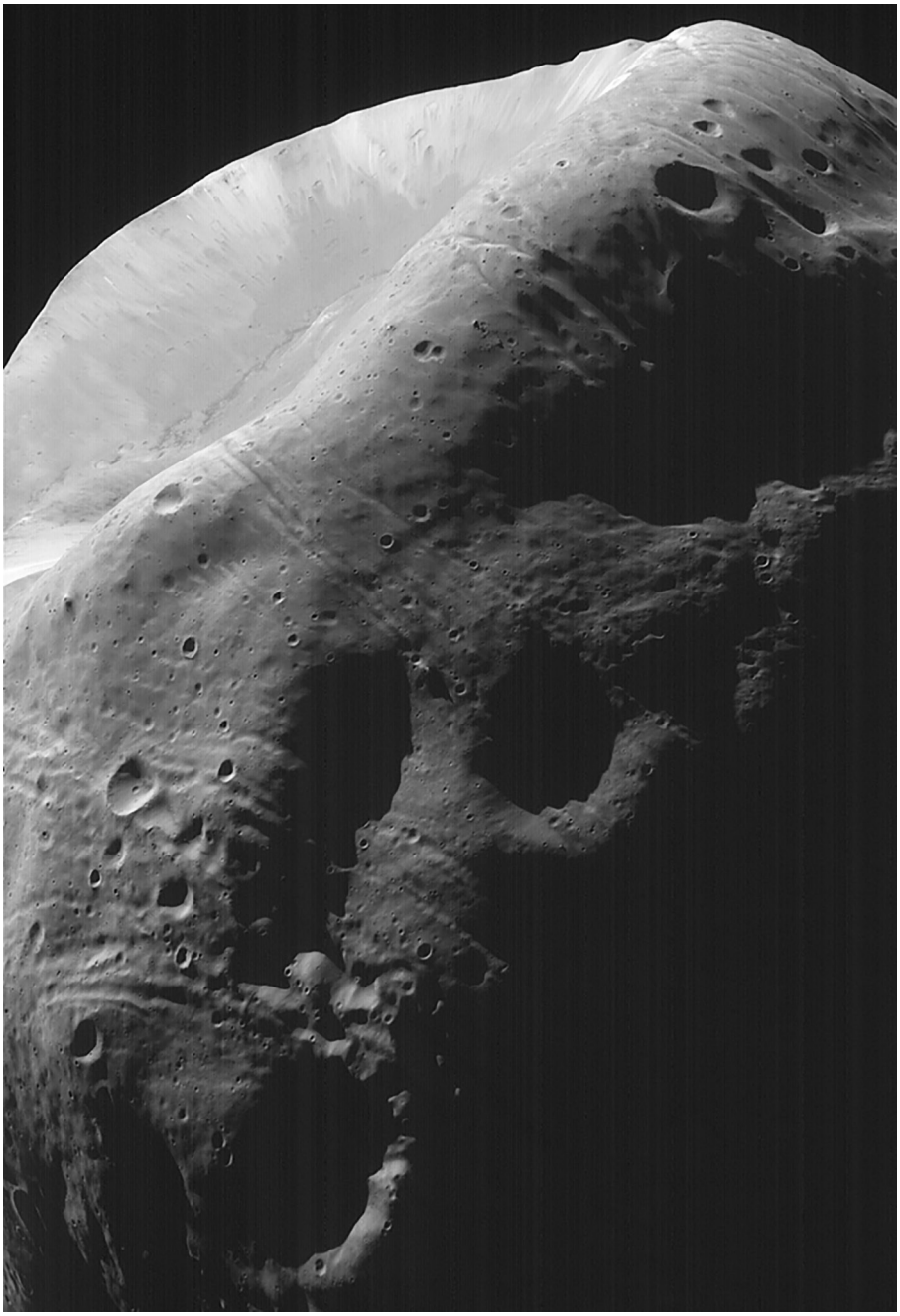
Two mysterious moons whirl around Mars. Despite the many missions to the planet, not a single one has focused on its satellites—or, rather, not a single successful one. Three previous Martian moon explorers, launched by Russia or the Soviet Union, all failed. Now Japan is trying its luck with a high-risk venture that aims to grab rocks from the larger Martian moon and bring them to Earth for laboratory analysis.

"It's a very scary mission," says Tomohiro Usui of the Japan Aerospace Exploration Agency (JAXA) in Sagamihara. The spacecraft's daunting tasks will include multiple touchdowns on a heavily cratered world. The chief goal is to settle a debate over the origin of the moons (1). Did the Red Planet steal them from the asteroid belt, or did they form after an asteroid smashed into Mars? The answer carries implications for satellites elsewhere and perhaps even for the origin of water on Earth.



In 1998, the Mars Global Surveyor captured rare images of Mars moon Phobos (pictured). Little is known about either it or its companion moon Deimos. Image credit: NASA/Jet Propulsion Laboratory/Malin Space Science Systems.

Discovery and Controversy

Astronomers have known of the two tiny moons ever since the 19th century. Using a newly built 26-inch telescope, Asaph Hall at the US Naval Observatory in Washington, DC, spotted them in 1877—a year when Mars passed exceptionally close to Earth. That's also when another astronomer, Giovanni Schiaparelli, claimed to see "canali" (canals or channels) crisscrossing the planet. Though less sensational, Hall's discovery proved more enduring.

His motivation actually came from Saturn. The year before, Hall had discovered that the Ringed Planet spun faster than books of the time had said, leading him to question their claims that Mars had no moons. Still, Hall knew his hunt for new moons would be difficult; any unseen satellites orbiting such a nearby planet must be small and dim. Indeed, he almost gave up the search, persevering only at his wife's urging. Shortly after her encouragement, Hall discerned two faint points of light beside the brilliant planet's glare. He christened the moon that lay closer to Mars Phobos (meaning fear) and the farther one Deimos (terror), apt companions for a planet named after the Roman god of war.

For another century, Phobos and Deimos remained nothing more than dim dots seen through telescopes. In the 1970s, NASA's Mariner 9 and Viking spacecraft provided the first close-up views. Both moons turned out to be dark, potato-shaped, and

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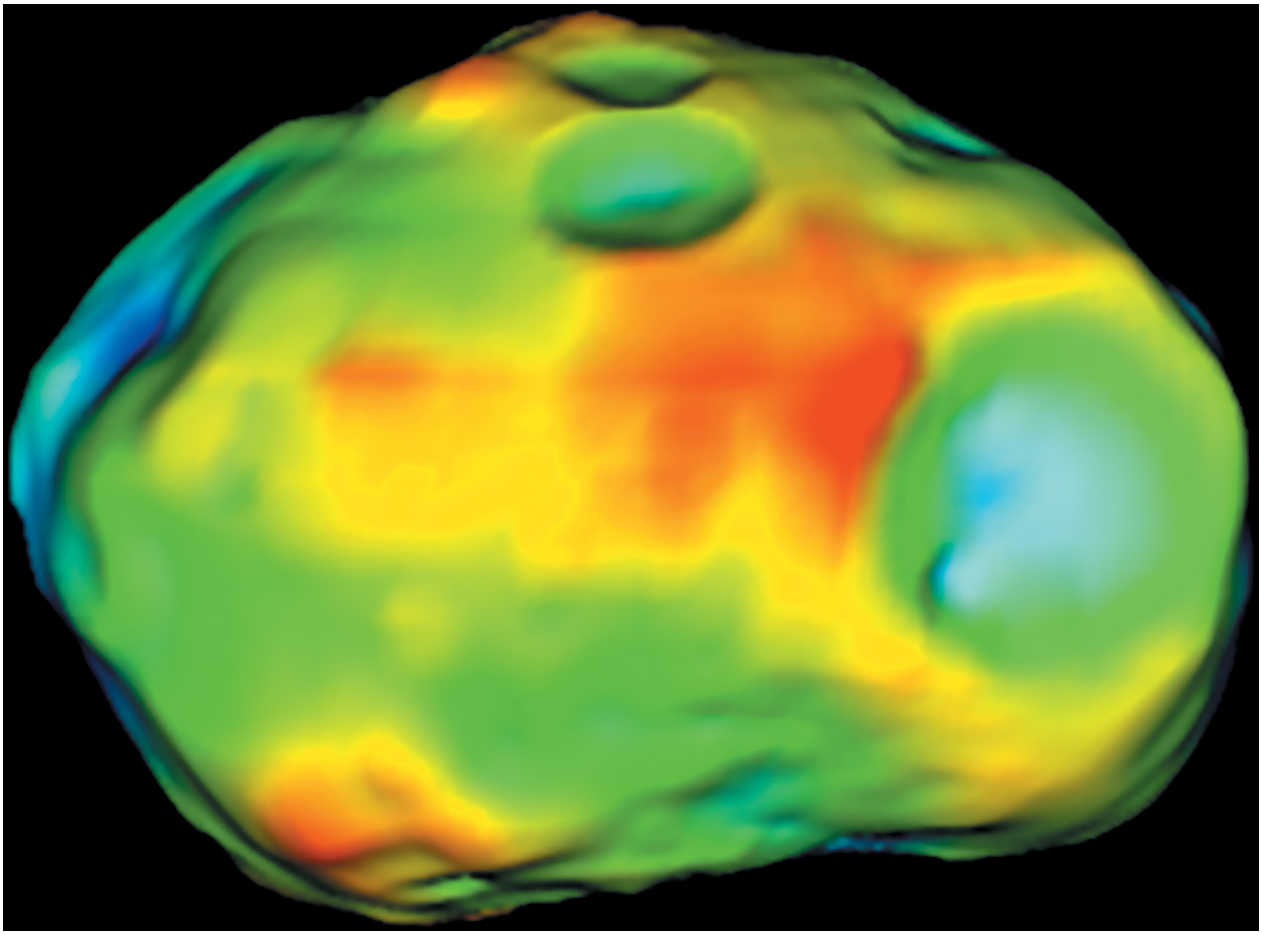

In this topographic map of Mars moon Phobos, red represents the highest altitudes and blue the lowest. The relative heights are affected by the object's own gravity, effects of its spin, and tidal forces from Mars. Image credit: Peter Thomas (Cornell University, Ithaca, NY).

crater-pocked. The longest axis of Phobos measures only about 16 miles; that of Deimos, about 10 miles. Phobos sports a huge crater, which resulted from a collision with an asteroid that nearly shattered the moon altogether. In honor of Hall's wife, that crater is called Stickney, her maiden name. A smaller crater on Phobos is called Hall.

Both moons look like asteroids, many of which are also dark, potato-shaped, and crater-pocked. What's more, the asteroid belt is next door, wending its way between the orbits of Mars and Jupiter. So researchers have long considered Phobos and Deimos to be asteroids that Mars snatched for itself when they strayed too close. "I think that the preponderance of the data is consistent with captured asteroids," says Scott Murchie at Johns Hopkins Applied Physics Laboratory in Laurel, MD. In particular, the spectra of Phobos and Deimos resemble those of dark, carbon-rich meteorites that come from carbon-rich asteroids.

Nevertheless, he acknowledges that this theory has a problem. The orbits of Phobos and Deimos around Mars show no signs of their capture. Captured moons should have highly elliptical orbits tilted at great angles relative to their planets' equators; Phobos and Deimos do not. Their orbits are nearly circular and lie close to the Martian equatorial plane. Furthermore, whereas most captured moons, such as the ones orbiting Jupiter and Saturn, lie far from their planets, Phobos and Deimos are very close to theirs. Phobos is so close that the satellite circles Mars in less than 8 hours. Moreover, that moon's orbit is slowly shrinking. Within just 40 million years, Phobos will sink so close to Mars that the planet's tides will tear the small moon apart, raining debris onto the Martian surface.

In the early 1990s, Robert Craddock, a planetary scientist at the Smithsonian Institution's National Air and Space Museum in Washington, DC, suggested an alternative origin story. He drew on a theory that two groups of researchers had made two decades earlier, following the Apollo Moon missions. They had proposed what is now the standard view for the birth of Earth's Moon: It formed after a huge object slammed into our planet, kicking up debris that conglomerated into a large satellite (2, 3).

Craddock thought a similar idea could explain the much smaller moons of Mars, but he encountered fierce opposition. "I really couldn't understand the resistance I was getting," he says. "It was pretty disheartening." Several scientific journals rejected his work. All that appeared was an unrefereed abstract in 1994 (4).

Years later, after attending a talk on the subject that mentioned his work—and after many of his critics had either retired or died—Craddock tried again to publish, and in 2011, he succeeded. His paper showed how an object with a sixth of the mass of Earth's Moon could have created the Martian satellites when it hit the Red Planet (5). The impact theory naturally explains why Phobos and Deimos have such regular orbits: If they formed from a disk of debris that encircled the

planet's equator after the impact, they would have acquired the circular paths of the material in the disk.

Since then, other research teams have conducted computer simulations of this scenario, verifying that a giant impact on Mars can indeed create moons like Phobos and Deimos (6–8). The collision may even have spawned additional moons, which later crashed into the planet below. However, simulations alone don't prove that this scenario is what actually happened. So ascertaining the origin of the Martian moons is the chief scientific objective of Japan's new spacecraft.

The MMX Mission

Japan is launching the Martian Moons Exploration (MMX) spacecraft in 2024. The country's only previous Mars mission, a quarter-century ago, suffered a series of malfunctions and failed to enter orbit. Since then, however, Japan has successfully gathered rocks from two small asteroids, a feat it hopes to repeat at Phobos.

The new spacecraft will reach Phobos and Deimos in 2025, orbiting first the larger satellite and then the smaller. For 3 years it will take images and record spectra. An American-built gamma-ray and neutron spectrometer will measure abundances of key chemical elements. If the moons are, in fact, captured asteroids, elements and molecules that planetary scientists classify as volatile—easily vaporized, such as hydrogen and water ice—should be more abundant than if the moons formed after a giant impact. That's because the heat of an impact should have fried the volatiles away.

The most important and daring phase of the mission will occur when the spacecraft is close to Phobos: collecting rocks from the satellite below. A small rover, built by France and Germany, will separate from the mothership and land. The rover will study the site's mineral makeup and obtain data needed for the mothership's safe touchdown—such as determining how rigid or fluffy the surface is. Then the mothership itself will land near the rover. "This is very challenging," Usui says. After all, the spacecraft could crash into the surface or get stuck in the sand. If the mothership succeeds, it will then gather at least 10 grams of Phobos material. After spending 2 or 3 hours on the surface, the spacecraft will lift off, leaving the rover behind, and land elsewhere on Phobos, collecting another 10-gram sample. Finally, after orbiting Deimos, the spacecraft will head home, delivering the samples to Earth in 2029.

Analyzing those samples in a terrestrial laboratory will reveal the satellite's true origin, according to both Murchie and Craddock. "The chemistry of the return sample will be the crucial evidence," Usui says. In particular, the isotopic composition of the material—for example, the relative amounts of oxygen-16, oxygen-17, and oxygen-18—will pinpoint whether Phobos is made of asteroid material or Mars material, which have distinct isotopic ratios.

"Either way, I'm happy," Usui says. If Phobos and Deimos turn out to be captured asteroids, he expects a gold mine for theorists, as they'll have to explain how Mars could capture two bodies into such regular orbits. Perhaps the primordial Martian atmosphere extended so far out that the moons rubbed against it, transforming their initially elliptical orbits into the circular ones they have today. It would also mean that volatile-rich asteroids made their way inward from the asteroid belt to Mars. That suggests that other ice-rich asteroids voyaged even farther inward, to Earth, which could help to explain how water appeared on our planet.

On the other hand, if the giant impact theory proves correct, it will mean that all three moons in the inner solar system formed the same way, from giant impacts—even though Earth's Moon is one of the largest satellites in the solar system and the Martian moons are two of the smallest.

"Out of all the planetary missions that we have planned in the near future, I'm most excited about this," says Craddock, who is not part of the new mission. Great challenges will confront the scientists and engineers attempting the feat, but Craddock is "very optimistic that they can pull this off."

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