

Mars: The Piston and the Ring

How a fast, expanded Mars launched Deimos and Phobos

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Abstract

Phobos and Deimos circle Mars on near-circular orbits above its equator, one inside and one outside the corotation radius. Deimos is smooth and rounded; Phobos is scored by long grooves. Both are light and porous. Mars lost most of its water, yet a large reservoir of liquid water lies today 11.5–20 km beneath its crust.

We propose that both moons were fired from the same volcano, Pavonis Mons, by a young Mars that was expanded to 1.5 times its present radius and turned once in five hours. At its equator anything that left carried a free sideways speed of 1.78 km s^{-1} , and the effective gravity was a quarter of today's. Beneath a sealed, cooled crust the planet held water, volatiles and gas. Pavonis then stood about 30 km high, and steam carrying rock fragments had drilled a conduit through its whole height. As in a tube of ointment in which a trapped air bubble suddenly spits a drop, the trapped gas pushed a soft plug of crust from the base of that conduit to its top, as a piston is pushed along a cylinder, in less than a minute. Rising through a dense steam atmosphere that turned with the planet, the plug was carried round with it and needed an outward speed of only $1.3\text{--}1.5 \text{ km s}^{-1}$ to reach the ring, $1.9\text{--}2.4$ without that help. Deimos was the first plug, small and light; Phobos the second, larger and harder.

A plug reaches the ring, just beyond the corotation line at 7,057 km, without all the sideways speed it needs to stay there. The missing speed came from a ring that Mars had built from its own steam long before. Below the line the steam turned with the planet as an atmosphere; at the line, where turning with Mars is already an orbit, it left the atmosphere, condensed into ice crystals and dust, and formed a ring. A body crossing the ring is dragged forward toward the ring's speed: it gains its orbit, rounded and equatorial, and the same friction grinds it. Beyond the corotation line the tide of the young, soft, fast Mars then pushed each moon outward. Deimos was fired first and passed the line's final place, 20,428 km, before the line got there; it stayed long in the ring and was ground smooth, mostly in the clumpy outer ring at the end of its climb. Phobos, dragging on the walls of the conduit, was braked: it reached only the thin, gaseous edge of a waning ring, was etched without being smoothed, and kept its grooves. The line, moving outward as Mars slowed, caught it near 19,000 km, and it has been falling since. The inner part of the ring fell back onto Mars as dust; the rest evaporated to space, and the water that never left stayed trapped beneath the sealed crust. The mass and gas that left Mars carried its spin with them, and the planet slowed and contracted to its present state.

Part I tells this sequence. Part II sets out the evidence that remains: the conduit of Pavonis Mons, the two faces of the moons, their orbits, and the water. Part III gives detailed predictions, each with its value, the instrument that will measure it, the date, and what the accepted explanation expects at the same place — among them the samples of Phobos that the Martian Moons eXploration mission is to return in 2031.

Keywords: Mars; Phobos; Deimos; Pavonis Mons; volcanic conduit; circumplanetary ring; corotation radius; tidal evolution; MMX

WHAT THIS PAPER PROPOSES

One volcano, two shots, one ring. A fast, expanded, water-rich Mars fired two crustal plugs from one conduit at Pavonis Mons by trapped gas. A ring of condensed steam completed their orbits and ground the first of them; the tide pushed both outward. Deimos, first and long in the ring, is smooth, rounded, smaller than it left, and on a circular orbit beyond the line. Phobos, second, braked in the conduit, met only the thin inner edge of a waning ring: it was etched by gas, not smoothed by water, kept its grooves and wrinkles, and was caught by the moving line and began to return.

What the account requires — stated once here, collected in Part O:

- A young Mars about 1.5 times today's radius with a 5-hour day, and the later loss of about 92% of its spin (§H, O).
- A Pavonis about 30 km high, a conduit drilled through its height by steam and rock fragments, and a soft plug that seals it; trapped gas at 0.5–0.9 GPa driving the plug up the conduit in less than a minute, with walls that hold that pressure for that time (§C). This is the critical step.
- A soft young Mars, dissipating 8 to 20 times more than today for half a billion to a billion years (§G.2).
- A dense steam atmosphere turning with Mars below the corotation line, and above it a ring of condensed steam, built by Mars before the shots, able to give each body the sideways speed it still lacks: from a few per cent to about half of its mass in perfect coupling, more in practice (§E, F). The account stands or falls with the ring.
- An explanation of the dark, primitive-looking spectra of both moons in terms of Martian material altered by water and space.

The working environment

The young Mars of this paper is not the Mars of today. Every number below belongs to it unless the row says “today”. The paper keeps one rule throughout: a body that leaves a spinning planet carries the sideways speed of the point it left from. On a planet that turns once in five hours, that sideways speed is large, and it changes what a volcano can do.

Quantity	Value	Role
Mass of Mars	$M = 6.4171 \times 10^{23} \text{ kg}$	Fixed throughout; $GM = 42,828 \text{ km}^3 \text{ s}^{-2}$
Radius, today	3,389.5 km	The reference
Radius, young Mars	$R_0 = 1.5 \times 3,389.5 \approx 5,084 \text{ km}$	The author's estimate of the expanded, hot, volatile-rich planet (§B.1)
Mean density, young Mars	$\approx 1,170 \text{ kg m}^{-3}$	Follows from mass and radius
Day, young Mars	5 h	The second input (§B.2)
Day, today	24.62 h	Sidereal rotation
Equatorial sideways speed	$v_t = \omega R_0 = 1.78 \text{ km s}^{-1}$	Given free to anything that leaves the equator
Effective equatorial gravity	$1.66 - 0.62 = 1.04 \text{ m s}^{-2}$	Gravity minus the outward effect of the spin; about 0.28 of today's 3.73
Corotation radius, young Mars	$7,057 \text{ km} = 1.39 R_0$	Where turning with Mars is already an orbit
Corotation radius, today	20,428 km	Phobos inside it, Deimos outside
Phobos today	$a = 9,375 \text{ km}$, $e = 0.0151$, $i = 1.09^\circ$, period 7.65 h, 2.14 km s^{-1} , $5,740 \text{ km}^3$, $1,853\text{--}1,887 \text{ kg m}^{-3}$	Falls; 3.2 orbits per Martian day
Deimos today	$a = 23,463 \text{ km}$, $e = 0.0003$, $i \approx 1.8^\circ$, period 30.3 h, 1.35 km s^{-1} , $\approx 1,000 \text{ km}^3$, $1,471 \text{ kg m}^{-3}$	Recedes; 0.8 orbits per Martian day
Launch site	Pavonis Mons, 1.48°N , 247.04°E ; caldera 47 km wide, nearly 5 km deep	The conduit (§D, §I)
Height of Pavonis, young Mars	about 30 km (14 km today)	It shared the expansion; its conduit runs through its height (§B.5)
Inner edge of the ring	the corotation line, 7,057 km	Below it the steam is an atmosphere turning with Mars (§F.1)

What happened

A The puzzle

A.1 Two moons on two sides of one line

Phobos and Deimos are small, dark and light. Phobos is about 22 km across, Deimos about 12; their bulk densities, 1,853–1,887 and 1,471 kg m⁻³, mean that a third to a half of each body is empty space (Pätzold et al. 2025; NASA/JPL Solar System Dynamics). Both circle Mars almost exactly above its equator on almost circular orbits. Phobos, at 9,375 km from the centre, goes round in 7.65 hours, three times in each Martian day; Deimos, at 23,463 km, takes 30.3 hours.

Between them runs the corotation radius, 20,428 km, the distance at which a body going round Mars keeps pace with its rotation. Inside it a moon outruns the planet and the tide it raises holds it back: Phobos is spiralling down. Outside it the tide draws a moon forward: Deimos is slowly receding. Any account of the moons has to put Phobos inside the line and Deimos outside it.

A.2 Two faces

The two moons do not look alike. Deimos is smooth: its craters are shallow and worn, its outline softened. Phobos is rough: long parallel grooves run across it, chains of pits run along the grooves, and the 9-km depression Stickney opens on its leading side (Thomas et al. 1979; Basilevsky et al. 2014). An account of the origin should say why two bodies of the same planet carry such different surfaces.

A.3 The water of Mars

Mars once had rivers and lakes. Its atmosphere today is enriched in heavy hydrogen about six to seven times relative to the Earth's oceans, the signature of a long loss of water to space; the early planet held at least the equivalent of a global layer 137 m deep (Villanueva et al. 2015). Yet the seismometer of the InSight lander found that the mid-crust beneath it, between 11.5 and 20 km depth, is best explained by rock whose pores are full of liquid water — enough, if the same holds across the planet, for a global layer 1–2 km deep (Wright, Manga & Panning 2024). Mars lost much of its water and kept much of it. An account of the moons that involves water should say where each part went.

A.4 The accepted explanations

Three origins are discussed today. **Capture** of two small asteroids fits the dark colour but not the orbits: a captured body arrives on an inclined, eccentric orbit, and turning two such orbits into equatorial circles has not been shown to work. **A giant impact** on Mars throws up a disc of debris from which the moons accrete; a disc settles into the equator and explains the orbits well, and it is the leading account (Rosenblatt et al. 2016; Hyodo et al. 2017; Canup & Salmon 2018). **Ring-moon cycles** let moons fall, break into rings and re-form (Hesselbrock & Minton 2017). In all three, the different faces of the two moons are explained separately, by tides, by ejecta from Stickney or by later impacts (Hurford et al. 2016; Ramsley & Head 2019).

TODAY AND IN THIS PAPER

Today: the moons accreted from debris thrown up by a foreign body; their faces have separate causes. **Here:** the moons are plugs of Martian crust fired from one volcanic conduit by trapped gas, given their orbits and their faces by one ring that Mars had built from its own steam.

B The young Mars

B.1 Expanded by half

A young, hot planet full of volatiles is larger than the cold body it becomes. We take the young Mars to have been 1.5 times its present radius, $R_0 \approx 5,084$ km. Its mass is that of Mars today, so its mean density was

$$\bar{\rho} = \frac{3M}{4\pi R_0^3} \approx 1,170 \text{ kg m}^{-3}, \quad (1)$$

about 0.3 of today's 3,934. This is the planet as a hot, swollen body of melt, gas and water beneath a crust that had begun to cool and seal.

B.2 A five-hour day

The young Mars turned once in five hours, $\omega = 2\pi/(5 \text{ h}) = 3.49 \times 10^{-4} \text{ s}^{-1}$. A point on its equator moved sideways at

$$v_t = \omega R_0 \approx 1.78 \text{ km s}^{-1}. \quad (2)$$

This speed is given free to everything that leaves the equator. A body thrown out of the planet does not leave from rest: it leaves with the speed of the ground beneath it, as a ball dropped from a fast carousel flies forward and outward at once.

B.3 A quarter of the weight

At the expanded equator gravity was $GM/R_0^2 = 1.66 \text{ m s}^{-2}$, and the spin pushed outward with $\omega^2 R_0 = 0.62 \text{ m s}^{-2}$. What held a body down was the difference,

$$g_{\text{eff}} = \frac{GM}{R_0^2} - \omega^2 R_0 \approx 1.04 \text{ m s}^{-2}, \quad (3)$$

about 28% of today's 3.73. A plug of crust on the equator of the young Mars weighed little more than a quarter of what it would weigh today.

B.4 The line close to the ground

The corotation radius of this Mars was

$$r_{\text{co}} = \left(\frac{GM}{\omega^2} \right)^{1/3} \approx 7,057 \text{ km} = 1.39 R_0, \quad (4)$$

less than 2,000 km above its surface. Today the line stands 17,000 km above the ground.

B.5 A taller volcano

Pavonis Mons rises about 14 km above the mean surface of Mars today. On the expanded Mars it stood higher. It shared the expansion of the planet, which alone makes it about 21 km, and its summit, a dome swollen with gas and melt over an active conduit, stood higher still: we take about 30 km. The height matters little for the launch itself — at the summit the sideways speed is 1.785 km s^{-1} and the effective gravity 1.01 m s^{-2} — but it matters for the conduit, which runs through the whole height of the volcano (§C.4). When Mars contracted, the volcano contracted with it.

Quantity	Today	Young Mars	Change
Radius, km	3,390	5,084	×1.5
Day, h	24.6	5	×0.20
Free sideways speed at the equator, km s^{-1}	0.24	1.78	×7.4
Effective gravity at the equator, m s^{-2}	3.72	1.04	×0.28
Corotation radius, km	20,428	7,057	×0.35
Height of the line above the ground, km	17,040	1,973	×0.12
Height of Pavonis Mons, km	14	about 30	×2

Table 1. The young Mars against Mars today. The colour deepens with the size of the change.

c The gas push

C.1 A tube of ointment

The idea began at home. Squeezing a tube of ointment a little at a time, and letting go each time, lets the tube draw a bubble of air back through its nozzle. At the next squeeze the finger presses not on the ointment but on the bubble, which compresses like a spring; when the bubble reaches the nozzle it releases all at once and spits the drop at the tip out with force. The drop was not thrown by the finger. It was thrown by gas that had been trapped, compressed and released.

C.2 A planet under a lid

The young Mars held water, carbon dioxide and other volatiles in its hot interior, beneath a crust that had cooled from above and sealed. Gas rising from below could not escape through the sealed crust; it collected beneath it, in chambers and in the pipes of volcanoes whose tops had frozen into plugs. The planet was, in the image of the tube, full of trapped bubbles under a lid.

C.3 Why a confined push and not a blast

A volcanic explosion that releases gas freely cannot throw rock to space: the gas expands in every direction and its speed is bounded by the speed of sound in the hot gas, of order 1 km s^{-1} . For steam at 1,500 K,

$$c_0 = \sqrt{\frac{\gamma RT}{\mu}} \approx 0.95 \text{ km s}^{-1} \quad (\gamma \simeq 1.3, \mu = 0.018 \text{ kg mol}^{-1}). \quad (5)$$

A volcanic conduit changes this. When trapped gas pushes a plug along a closed conduit, the conduit acts as a cylinder and the plug as a piston: all of the pressure acts on the plug for the whole length of the barrel, and nothing is lost sideways. This is the principle of the gas gun, and its limit is the speed at which the gas itself can expand into empty space,

$$u_{\max} = \frac{2c_0}{\gamma - 1} \approx 6.3 \text{ km s}^{-1} \quad \text{for steam at 1,500 K,} \quad (6)$$

5.7 km s^{-1} at 1,200 K and 7.3 at 2,000 K. The launch speeds that Part E requires, 1.3 – 2.4 km s^{-1} , lie well below half of this limit. The confined push does not break the physics of gas; it uses all of it.

C.4 The cycle that builds a plug

The cycle is that of a Vulcanian eruption, seen today at volcanoes such as Sakurajima and Soufrière Hills (Clarke et al. 2015). Gas escapes, and the conduit empties. In the pause that follows, magma standing in the conduit loses its gas and cools; the conduit is open to the sky above it, and its upper part hardens into a plug. A weak pressure from below cannot move the plug. The plug goes on cooling and strengthening while gas gathers beneath it and its pressure rises, until the plug gives way and is driven upward from below, as water is driven out of a geyser. Each cycle builds a new plug. A longer pause gives a plug that has cooled deeper: larger and harder.

Each release also deepens the conduit. Steam leaving at high speed carries fragments of rock, and the mixture drills and widens the pipe it passes through, as gas-charged eruptions on the Earth drilled the kimberlite pipes and the diatremes of maar volcanoes. Over many cycles the conduit of Pavonis was drilled through the whole height of the volcano, about 30 km, from the chamber at its base to the summit.

C.5 A soft plug seals

The plug is not a block of cold rock. It is warm, viscous, water-rich material: under a slow load it flows, presses against the walls of the conduit and fills every crack, as a rubber stopper seals a bottle; under a sudden load it moves as one body. It therefore needs no strength to hold the gas: it holds the gas because it is pressed against the walls, not because it resists breaking. The moons themselves show that they were soft. Their oldest hollows, Stickney among them, were not dug into bowls but folded inward (§K.3, §L), and a third to a half of each body is the empty space of a foam that froze (§J.3).

The plug formed at the base of the conduit, about 30 km below the summit, where the rising melt met the cooler walls. There its front stayed warm and soft: had it stood at the open top, it would have dried, cooled and hardened in the air, and could not have folded under a blow. It stayed soft until the shot and for long afterwards: a shell a kilometre thick takes tens of thousands of years to cool.

C.6 How hard the gas must push, and what holds it

A plug of length L_p and density ρ_p driven to speed v along a conduit of length L_b needs a mean pressure

$$\bar{p} \approx \frac{\rho_p v^2 L_p}{2L_b} + \rho_p g_{\text{eff}} L_p, \quad (7)$$

the first term to accelerate it, the second to carry its weight. The weight is small: on the young Mars it adds about 0.02 GPa. What sets the pressure is the speed, which Part E derives: 1.3–1.5 km s^{−1} if the atmosphere carries the plug round as it rises (§E.2), 1.9–2.4 km s^{−1} if it does not. We take Deimos 14 km long at 1,200 kg m^{−3} and Phobos 18 km long, along its short axis, at 1,600 kg m^{−3}.

Conduit	Deimos, carried round	Phobos, carried round	Deimos, free flight	Phobos, free flight
20 km	0.96 GPa	1.29 GPa	2.47 GPa	2.64 GPa
30 km	0.65 GPa	0.87 GPa	1.65 GPa	1.77 GPa
40 km	0.49 GPa	0.66 GPa	1.24 GPa	1.33 GPa

Table 2. Mean gas pressure behind each plug, for a Pavonis 30 km high and a five-hour day. "Carried round": the plug rises turning with the atmosphere (§E.2); "free flight": no help from the atmosphere. Around the base of the conduit the rock presses back with 0.05–0.10 GPa; the wall of a pressurised conduit holds about twice that, plus the strength of the rock, some 0.1–0.2 GPa. The colour deepens with the gap between the two.

The walls must therefore hold 0.5–0.9 GPa for less than a minute, three to five times what the surrounding rock alone presses back with. Three things close the gap. The crust of the young Mars was cold from above and thick, and cold, dense rock is several times stronger in compression than in tension. The soft plug seals the conduit as it moves, so that gas escaping into a crack does not outrun it. And the shot is short: a crack must open and grow along the wall before the gas can leave through it, while the whole push lasts 25–45 seconds. This is the step on which the account depends most.

C.7 Inside the conduit

Inside the conduit the plug turns with Mars. The spin pushes it outward at 0.62 m s^{-2} and gravity pulls it back at 1.66, so the gas works against a net 1.04 m s^{-2} at the base and 1.01 at the summit, which adds a few per cent to the pressures of Table 2. Along a conduit of 30 km the plug reaches its speed in 25–45 seconds, at a mean acceleration of three to ten times the gravity of the Earth.

The same turning presses the rising plug sideways. A body rising through a spinning planet keeps the sideways speed of the depth it left, which is less than that of the ground above it, so the conduit wall must push it forward: the Coriolis acceleration $2\omega v$ is $0.9\text{--}1.7 \text{ m s}^{-2}$ at these speeds, as large as the effective gravity, and it presses the plug against one wall of the conduit. A soft, light first plug slides along the wall; a larger, harder second plug drags on it, is scored along its length, and is braked (§K.1).

C.8 The energy of a shot

A plug of Deimos, about $2.4 \times 10^{15} \text{ kg}$ at $1.5\text{--}2.4 \text{ km s}^{-1}$, carries $2.7\text{--}7.0 \times 10^{21} \text{ J}$; a plug of Phobos, about $9.3 \times 10^{15} \text{ kg}$ at $1.3\text{--}1.9 \text{ km s}^{-1}$, $0.8\text{--}1.7 \times 10^{22} \text{ J}$. Steam at 1,500 K holds about $3 \times 10^6 \text{ J}$ per kilogram; at an efficiency of 40% the shots need $2\text{--}6 \times 10^{15}$ and $0.7\text{--}1.4 \times 10^{16} \text{ kg}$ of steam, about the mass of the plug. Against the water of the young Mars, of order 10^{23} kg , each shot spends about one ten-millionth of it.

THE CRITICAL STEP

The shot is the step on which the account depends most, and the one furthest from what volcanoes do today. On the Earth, Vulcanian blocks leave at hundreds of metres per second; here a plug leaves at $1.3\text{--}2.4 \text{ km s}^{-1}$. Five things make the difference, and each is stated with its number: a quarter of the weight (§B.3); the free sideways speed of 1.78 km s^{-1} (§B.2); a confined push, bounded by 6.3 km s^{-1} rather than by the speed of sound (§C.3); a conduit drilled through a volcano about 30 km high (§B.5, C.4); and an atmosphere that carries the rising plug round with the planet (§E.2). The account would fail if the walls of such a conduit could not hold 0.5–0.9 GPa for less than a minute, if a soft plug could not seal it, or if no mass deficit lay beneath the caldera of Pavonis (prediction N.4).

D The cannon

D.1 Why the equator

A body leaving Mars from latitude ϕ starts on an orbit tilted by ϕ to the equator. Both moons orbit within about two degrees of the equatorial plane. A launch site on the equator puts them there from the first moment; a site far from the equator would need something to flatten the orbit afterwards.

D.2 Four volcanoes, one candidate

The four great volcanoes of the Tharsis province are Olympus Mons and, on a diagonal line, Ascraeus, Pavonis and Arsia Montes. Pavonis Mons is the middle one, at 1.48°N , 247.04°E (IAU Gazetteer), the closest of the four to the equator. Its summit caldera is a single circular pit 47 km wide and nearly 5 km deep, with a larger, shallower depression about 90 km across beside it. Part II (§I) compares it with the other three.

D.3 One conduit, fired more than once

Olympus Mons, the largest volcano in the Solar System, lies at 18.65°N ; a body fired from it would start on an orbit tilted by about 19° . Gas rising from a deep chamber follows the conduit it has already opened, and while that conduit is active there is no reason for the pressure to build a second exit in another volcano. One conduit fired more than once. Pavonis, 1.48° from the equator, gives a starting tilt of about 1.5° , close to the tilt of Phobos today (§G.3).

D.4 One conduit, two plugs

The two moons left the same conduit one after the other. The first plug sat at the top of the pipe: small, light and wet, the youngest and most gas-filled material, driven by the full pressure of the chamber. It left cleanly, without dragging on the walls, and flew high. After it left, the rising melt cooled again in the open pipe and sealed it with a second plug, grown over a longer time: larger, drier and harder. The gas that built up beneath it fired Phobos; dragging on the walls of the conduit, it was scored along its length and braked (§K.1).

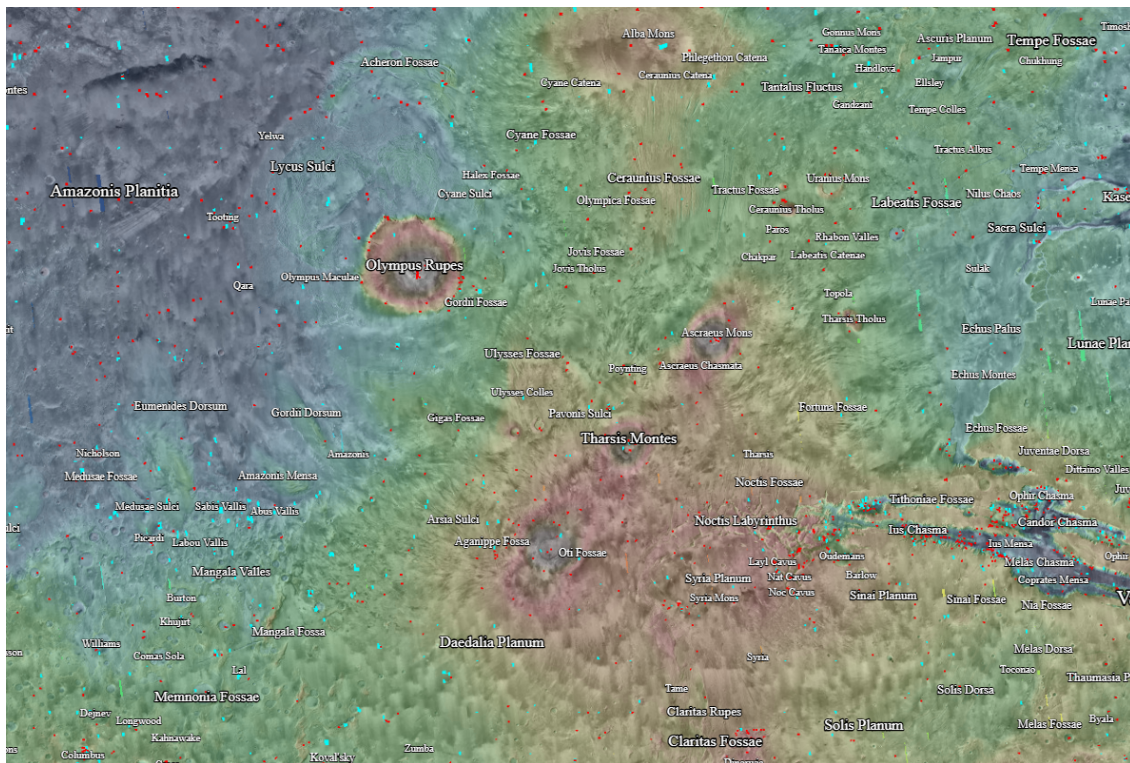


Figure 1. Pavonis Mons, the middle of the three Tharsis Montes, between Ascraeus Mons to the north-east and Arsia Mons to the south-west, at 1.48°N , 247.04°E , with its

summit caldera 47 km wide. Credit: ACT-REACT QuickMap Mars; MOLA colourised elevation (NASA/GSFC); IAU nomenclature.

E The shot

E.1 The speed budget

A plug leaves the summit, $R_1 = R_0 + 30$ km, with two speeds at right angles: the free sideways speed of the ground, $v_t = \omega R_1 = 1.785 \text{ km s}^{-1}$, and the outward speed given by the gas, v_r . In free flight, energy and angular momentum fix how high it rises. The outward speed that brings the top of its path to the radius r follows from

$$\frac{v_t^2 + v_r^2}{2} - \frac{GM}{R_1} = \frac{1}{2} \left(\frac{R_1 v_t}{r} \right)^2 - \frac{GM}{r}, \quad (8)$$

the left side being the energy at launch and the right side the energy at the top, where the sideways speed has fallen in proportion to R_1/r because the angular momentum $R_1 v_t$ is kept.

E.2 The atmosphere carries the plug round

The plug does not rise through empty space. Below the corotation line the young Mars was wrapped in the steam it gave off without pause: an atmosphere, dense and hot, turning with the planet (§F.1). A body that rises keeps its angular momentum and falls behind the turning gas around it, which moves faster the higher it lies; the gas presses on it from behind and drives it forward. If the atmosphere held the rising plug fully in step, it would arrive at the line already turning at the speed of an orbit, and the outward speed it needs would be set by the rotating frame alone,

$$v_r^2 = 2 \left[GM \left(\frac{1}{R_1} - \frac{1}{r} \right) - \frac{\omega^2}{2} (r^2 - R_1^2) \right] \quad (r \leq r_{co}), \quad (9)$$

continued in free flight above the line. The plug is heavy and the gas light, so the real help lies between the two cases; Table 3 gives both.

Shot	Top of path, km	Outward speed, carried round	Outward speed, free flight	Missing at the top, carried / free	Circular speed there
Phobos, the braked shot, just beyond the line	7,500	1.32	1.90	0.07 / 1.17	2.39
Deimos, into the ring	10,000	1.50	2.41	0.33 / 1.16	2.07

Table 3. What the gas must give, in kms^{-1} , for the five-hour Mars, launched from a summit 30 km high. Each plug needs only to reach the ring; the ring and the tide do the rest (§F, G). The braked second shot, Phobos, was the weaker.

E.3 The height is reached; the orbit is not

The plug reaches the ring without all the sideways speed it needs to stay there. In free flight Deimos at the top of its path, 10,000 km, moves sideways at 0.91 km s^{-1} , where a circular orbit needs 2.07. Left alone, it would fall back along an ellipse whose lowest point lies about 1,100 km from the centre of Mars, deep inside the planet; it would strike Mars again within one revolution, at another longitude because Mars turns beneath it. Carried round by the atmosphere, it would lack only 0.33 km s^{-1} and would no longer strike the planet, but its path would still be an ellipse that dips back into the atmosphere and loses speed there. In every case something at the top of the path must give the plug the sideways speed it lacks, round its orbit and hold it beyond the line.

F The ring

F.1 Steam from every fissure

The ring was not made by the volcano, and it was not made at the time of the shots. From the first stages of its life the young Mars released steam and fine material from every fissure and crack of a hot, sealed, spinning planet, most strongly near the equator, where the spin lightened the crust most. Steam that rises from the ground keeps the sideways speed of the ground, which is less than the speed of an orbit: below the corotation line it cannot orbit, and it stays above the planet as an atmosphere, held up by its own pressure and turning with Mars. At the line, turning with Mars is already an orbit. There the steam left the atmosphere, cooled, and condensed into ice crystals, droplets and fine dust: a ring, beginning at the line and spreading outward. Its inner edge stayed at the line, because material that spread inward entered the atmosphere, was braked by it and fell back as frost and dust (§H.1). Beyond about 13,000 km, the Roche limit for ice around Mars, its material gathered into clumps. The moons were fired long afterwards, into a ring that already stood around the planet.

F.2 The ring completes the orbit

The particles of the ring circle Mars at the speed of an orbit at their height. A slow body crossing the ring is struck again and again from behind by material moving faster than itself, and is dragged forward toward the ring's speed. This is the same physics by which gas and debris discs damp the orbits of bodies inside them. The drag acts in three ways at once: it adds the missing sideways speed, so that the body no longer falls back; it rounds the orbit toward a circle at the ring's height; and because the ring lies in the equatorial plane, it draws the orbit into that plane.

To give a body its missing speed Δv by perfect sharing of momentum, the ring must hand over a mass of at least $m \Delta v / v_{\text{ring}}$: from 0.03 of the body's mass, for Phobos fully carried round by the atmosphere, to about 0.56, for Deimos in free flight (Table 3). Real coupling is less than perfect, so the ring must hold several times that — of order 10^{15} – 10^{16} kg, a very small fraction of the water the planet lost. The ring is load-bearing: without it a plug fired from the surface falls back within one revolution, and the account fails (§O).

F.3 The ring polishes

The friction that gives the body its orbit is the friction that grinds it. Every grain of ice that pushes the body forward also chips it. A body that stays long in the ring is both carried into a circular orbit and worn smooth: its sharp edges are taken off, its cracks and grooves worn away, its craters softened, and its size reduced. A body that passes through the ring quickly gains speed but keeps its face.

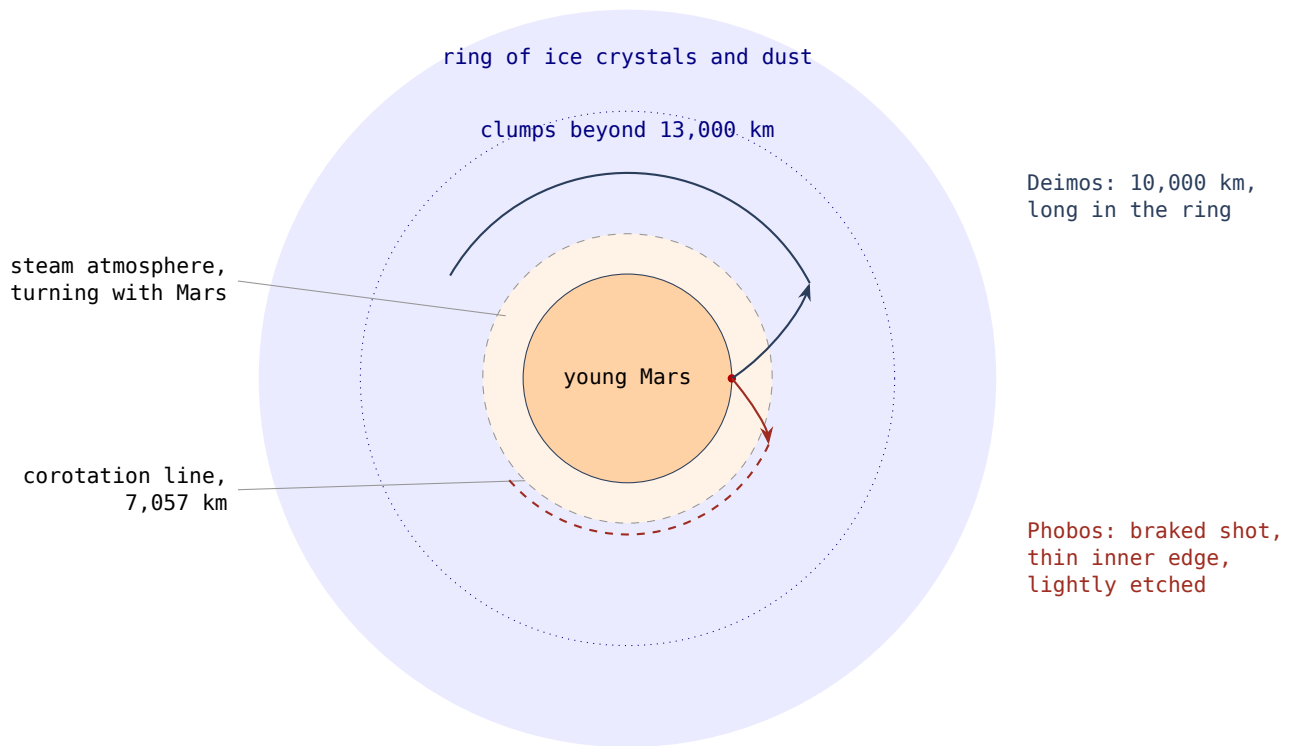


Figure 2. The geometry of the account (radii to scale, paths schematic). The plug leaves Pavonis with the sideways speed of the equator and the push of the gas, and rises through the steam atmosphere that turns with Mars below the line. Deimos rises into the ring and stays in it: it is carried into a circular orbit, pushed outward by the tide beyond the line, and ground in the clumpy outer ring. Phobos, braked and fired more weakly, enters the thin inner edge of a waning ring just beyond the line: it gains enough speed not to fall, is etched only lightly, and is pushed outward until the moving line catches it.

G Deimos first, Phobos second

G.1 Why Deimos was first

The first shot came when the chamber beneath Pavonis was at its full pressure and the first plug sat at the top of the pipe: small, light and water-rich. It left cleanly and was fired into a young, hot, fast Mars, with the ring at its fullest and the corotation line close to the ground, at 7,057 km.

G.2 Deimos: long in the ring

Deimos rose to the ring, about 10,000 km out, and stayed in it. The ring held it: it completed its orbit, rounded it and drew it into the equatorial plane, far beyond the

corotation line of its time. Beyond the line a moon goes round more slowly than the planet turns; the bulge it raises on the planet is carried ahead of it and pulls it forward, and it recedes. On the young Mars — 1.5 times larger, turning five times faster, soft and wet — this push was far stronger than today. A Mars that dissipated 8 to 20 times more than it does now carries Deimos from 10,000 km to 23,463 km within half a billion to a billion years; the first part, to 15,000 km, takes only some 30–50 million years, because close to the planet the push is strongest. Deimos passed today's line, 20,428 km, before Mars had slowed to today's day, so that the line, moving outward behind it, never caught it. Today the same push is weak: about 150 km in 4.5 billion years.

The ring also ground it. Most of the climb is spent in its last part, near 20,000–23,000 km, where the push is weakest, and there, beyond the Roche limit for ice, the ring was dense with clumps. Deimos was worn mostly at the end of its climb. It left larger than it is now, and smooth, without grooves; it lost its outer layers and its sharp edges, and came out rounded (§J.2).

G.3 Phobos: a braked shot, the edge of the ring, and a race with the line

Phobos was the second plug, larger, drier and harder, and the second shot was the weaker: dragging on the walls of the conduit, it was braked. The gas drove it at $1.3\text{--}1.9\text{ km s}^{-1}$ (Table 3), and it rose only just beyond the line, to about 7,500 km. There it met the ring, but not as Deimos had: it entered the thin inner edge of the ring, next to the atmosphere, and at a time when the ring was past its peak. Carried round by the atmosphere on its way up, it lacked little of the speed of an orbit, and the thin edge gave it that much. Gas and water wear a surface differently. Water and ice smooth and round it, as a river rounds a pebble. Gas carrying fine dust does not smooth: it etches and roughens, as a sandblast frosts glass. The water-rich, condensed part of the ring lay higher, where Deimos was; at the thin, gaseous edge Phobos was etched lightly, roughened rather than smoothed, and kept its exit grooves, its wrinkles and its sharp-rimmed pits. It lost about 1% of itself, a layer of some 40 m. The gas also turns about Mars in horizontal circles and damps the up-and-down motion of a tilted orbit. Phobos left Pavonis tilted by about 1.5° ; the damping weakens as the tilt shrinks, the ring faded first, and Phobos kept 1.09° — partly straightened, as it was partly worn.

Beyond the line the tide pushed Phobos outward, as it pushed Deimos. But Mars was slowing — the ring and the volatiles were leaving and carrying its spin away — and the line moved outward with it. Phobos receded more slowly than the line moved. The line caught it near 19,000 km, when the Martian day was about 22 hours, before reaching its final place at 20,428 km. From that moment Phobos was inside the line, and inside the line the tide drags a moon down: it began to return. Close to the line the tide almost vanishes, so Phobos lingered there for a long time, and most of its fall came late. Deimos had been fired earlier, with the line far behind it, and passed 20,428 km before the line got there.

Running its fall backwards at the tidal friction measured for Mars, $k_2/Q = 1.816 \times 10^{-3}$, puts Phobos at 18,800 km 3.5 billion years ago, 19,100 km 3.9 billion years ago and 19,500 km 4.5 billion years ago (Table 6, Part II). The tide has since rounded its orbit (its eccentricity is now 0.015) and brought it down to 9,375 km, where it goes round 3.2 times in each Martian day.

ONE ENCOUNTER, TWO FACES

Long in the ring: full orbit, circular and equatorial, beyond the line; ground smooth, rounded and reduced. That is Deimos. **Braked, and at the thin edge of a waning ring:** enough speed not to fall, lightly etched by gas and not smoothed, pushed outward until the moving line caught it, then inside the line and falling ever since; grooves and wrinkles kept. That is Phobos.

H Afterwards

H.1 The ring goes to space

The ring did not last. Exposed to sunlight and the solar wind, its water was broken apart and its hydrogen escaped; the heavy isotope stayed behind preferentially, and the atmosphere and the water left on Mars became enriched in deuterium. The part of the ring inside the corotation line was drawn inward by the tide and fell back onto Mars, mostly near the equator, as frost and Martian dust; the outer part and the volatiles left. The tide adds a minute push to each part of the ring at every turn of the planet — some 1,750 turns a year on a five-hour Mars — and together with evaporation it removed the ring over hundreds of millions of years. Its pull grows with the mass of the body, which is why the moons moved first and the ring left later. The loss of the ring and of the atmosphere left the surface dry.

H.2 The water that never left

The water inside Mars did not have to come back in: most of it never went out. The steam that fed the ring and the gas that fired the plugs were the part of the volatiles that found a way out through fissures and conduits. The rest stayed sealed beneath the same impermeable crust that held the gas in the conduit, and remains there today, in the pores of the mid-crust where InSight found it.

H.3 Mars slows and shrinks

A 5-hour Mars of 1.5 times today's radius carries about 12 times the spin of Mars today. Contracting to its present size without losing any of it, it would turn once in about two hours, not 24.6. So Mars lost about 92% of its spin. Firing a plug straight up does not brake a planet; what brakes it is mass that leaves carrying the planet's sideways motion with it. Gas, steam and debris that left through the corotation line took the most spin per kilogram: of order 5–20% of the starting mass, mostly volatiles, had to leave this way for Mars to slow from five hours and contract to its present state; the lower value holds if the density of the young Mars rose toward its centre. As the spin fell, the line moved outward, from 7,057 km toward its present 20,428 km: it caught Phobos near 19,000 km and never reached Deimos.

THE SPIN BUDGET

Spin (angular momentum) is conserved for Mars together with everything that left it. In units of the spin of Mars today ($1.9 \times 10^{32} \text{ kg m}^2 \text{ s}^{-1}$):

Item	Spin
Young Mars, 1.5 times today's radius, 5-hour day	12.2
Left with gas, steam and the ring through the corotation line (5-20% of the starting mass)	11.2
Mars today	1
Carried by the two plugs at launch	$< 10^{-6}$
Phobos and Deimos in their orbits today	$\approx 1.4 \times 10^{-6}$
Returned to Mars by the fall of Phobos	$\approx 5 \times 10^{-7}$

The moons are a millionth of the budget: launching them did not brake Mars, and their orbits did not need Mars's spin. The ring gave them their orbital speed from spin it had itself taken from Mars, and lost to space far more than it gave. The budget closes on one requirement only — the volatiles that left through the line (SO).

PART II

The evidence

Part I told the sequence. Part II sets out what it left behind, place by place. Each section gives the observation, what the account of Part I says about it, and the numbers.

I The mountain

I.1 The conduit of Pavonis

Pavonis Mons rises about 14 km above the mean level of Mars on a base about 375 km wide. Its summit caldera is a single circular pit 47 km across and nearly 5 km deep — a steep-walled cylinder rather than a shallow bowl — with a broader, shallower depression about 90 km across immediately to its north-east (USGS/IAU Gazetteer; NASA/JPL). The ratio of depth to width, about 0.10, is the measure of how much the summit is a barrel.

Volcano	Latitude	Caldera width	Caldera depth	Form
Pavonis Mons	1.5°N	47 km	nearly 5 km	single deep circular pit
Olympus Mons	18.7°N	about 70 km (nested)	about 3 km	a complex of overlapping, stepped pits
Arsia Mons	8.4°S	about 110 km	to be measured	one broad pit
Ascraeus Mons	11.8°N	nested pits	to be measured	several overlapping pits

Table 4. The four calderas of Tharsis. Green marks the property the account needs: on the equator, narrow, deep. The depths marked "to be measured" can be read from MOLA topography.

I.2 The scale of the pit

The volume of the Pavonis caldera, taken as a cylinder 47 km wide and 4.8–5.0 km deep, is 8,300–8,700 km³. The two moons today hold 5,740 and about 1,000 km³, together 6,740 km³. The pit is of the scale of the two plugs. It is what collapsed after the shots, not a mould of the plugs, so it does not set their size.

I.3 The collapse

When a plug leaves a pressurised conduit, the chamber beneath it loses what held up its roof. The roof cannot stand; it falls in. A steep, deep, circular pit is what a chamber leaves when its roof collapses vertically. The account expects the gravity beneath the caldera to show the missing mass of a chamber that fired (prediction N.4).

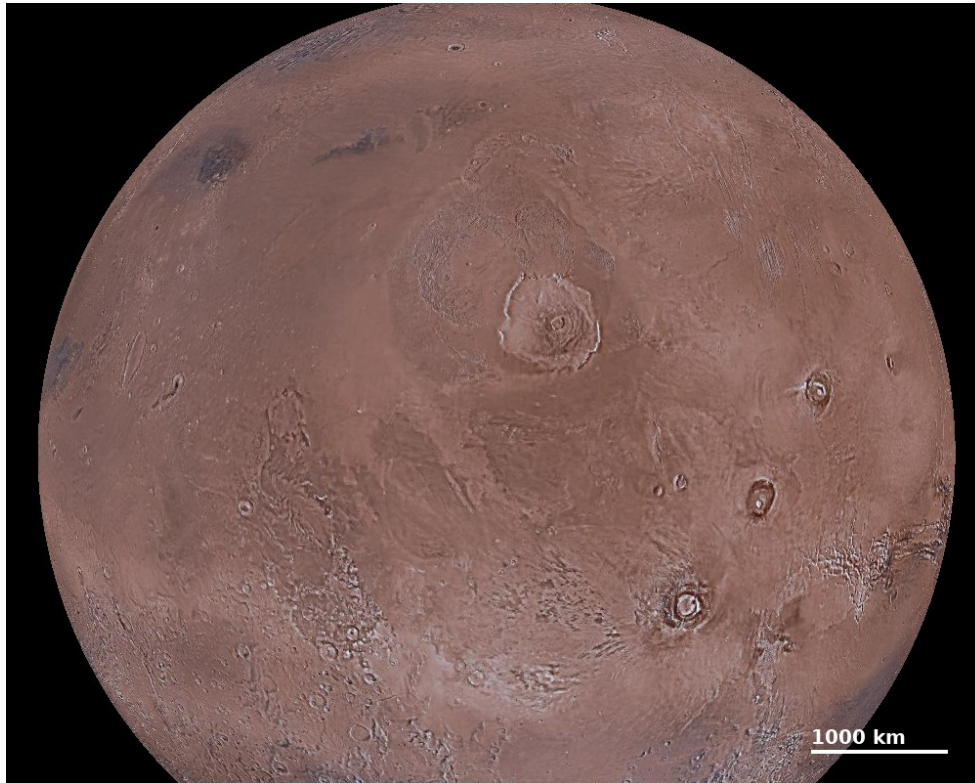


Figure 3. The Tharsis province, Viking colorised mosaic: Olympus Mons at upper left; Ascraeus, Pavonis and Arsia Montes on the diagonal. Pavonis, in the middle, sits closest to the equator. Credit: ACT-REACT QuickMap Mars; Viking Colorized Global Mosaic (NASA/JPL/USGS).

J Deimos

J.1 Smooth, rounded, circular

Deimos is the smoothest small body yet seen near Mars. Its depressions are shallow and worn; it has no grooves. Measured on the shape models of Ernst et al. (2023) in the same way for both moons, the depressions wider than 0.7 km on Deimos have a median depth of 1.9% of their width, against 5.5% on Phobos; 84% of them are shallower than 6% of their width, against 56% on Phobos, and only 3% are deeper than 12%, against 13%. Its orbit is almost a perfect circle (eccentricity 0.0003) close to the equatorial plane, and it lies beyond the corotation radius. These are the marks of a body that spent a long time in a ring: carried into a circular, equatorial orbit and worn by the same particles.

Deimos goes round more slowly than Mars turns, and it always has: at about 10,000 km it went round in 8.4 hours, against a Martian day of 5, about 0.6 times a day; today, at 23,463 km, it goes round in 30.3 hours against 24.6, 0.8 times a day. It has always

stood beyond the line. The line moved outward behind it and never caught it — the reverse of Phobos (§K.5).

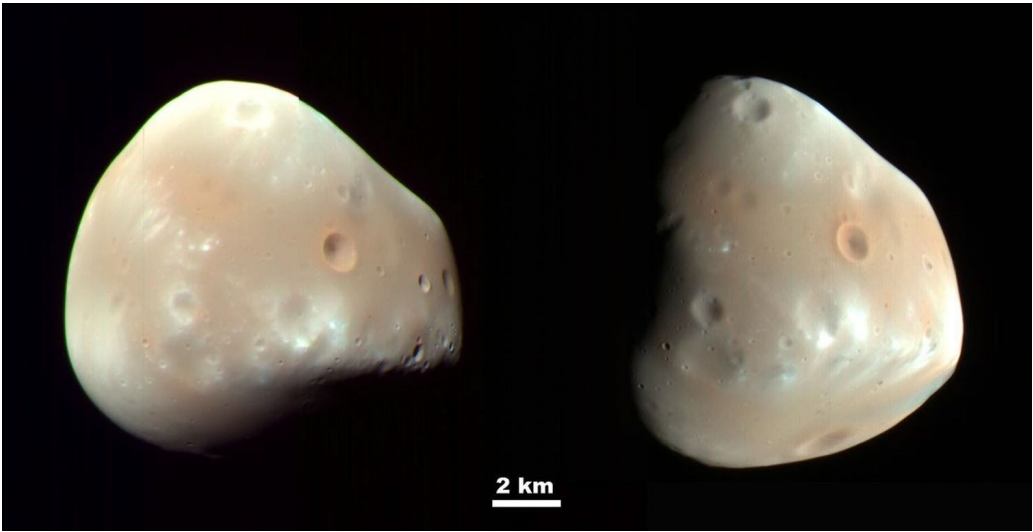


Figure 4. Deimos, HiRISE (two views; scale bar 2 km). A smooth, rounded body with shallow, worn craters and no grooves. Credit: NASA/JPL-Caltech/University of Arizona (PIA11826).

J.2 Larger when it left, but not larger than Phobos

Grinding removes material. Deimos left Pavonis larger than it is now, but not larger than Phobos, and it left smooth: the first plug did not drag on the walls of the conduit. How much it lost depends on how large it left:

Diameter on leaving	Volume, km ³	Share lost by today	Layer ground away
12.4 km (today)	1,000	—	—
14.0 km	1,430	30%	0.8 km
15.6 km	2,000	50%	1.6 km
16.8 km	2,500	60%	2.2 km
20 km	4,190	76%	3.8 km
22.3 km (as Phobos)	5,800	83%	4.9 km

Table 5. Deimos at departure: larger than today, not larger than Phobos. The colour deepens with the share ground away. The surviving roots of wrinkles favour the upper rows, a loss of 30–60%.

The same holds for its wrinkles. Deimos left hot and expanded like Phobos, cooled from the outside in, and wrinkled as its interior shrank beneath the hardened shell (§K.2). Deimos is not free of ridges; it lacks the large number that Phobos has (Thomas 1979). In the ring the high points are worn first: a ridge crest stands above its surroundings and meets the particles before the ground around it, so the ridges shrank faster than the body. In a layer of about a kilometre most of the wrinkles were erased; what Deimos shows today are the roots of the tallest, low and broad. They look small because they were ground with the body, not because they were born small.

J.3 Light and wet

Deimos is the lighter of the two, 1,471 against 1,853-1,887 kg m^{-3} . The first plug came from the top of the pipe, from the youngest, most water-rich and most gas-filled part of the planet; the second, drier and harder plug formed later and deeper in the emptied pipe. The order of the densities is the order of the shots. The moons are samples of the young Mars: a third to a half of each is empty space, a foam that froze, and their densities, 1,471 and about 1,860 kg m^{-3} , are those of the upper layers of a planet whose mean density was about 1,170 — light, porous and rich in water.

K Phobos

K.1 The exit grooves

Phobos is crossed by families of long, parallel grooves (Thomas et al. 1979; Murray & Heggie 2014). In the account of this paper they are first of all the marks of the shot: a hard, dry plug driven up a conduit, pressed by the Coriolis force against its western wall (§C.7) and dragging on it, is scored along its length, and the same drag braked it. They survived because Phobos met only the thin, gaseous edge of a waning ring and lost only about 1% of itself, a layer of some 40 m. Their survival is, in itself, the record of the push that fired it.



Figure 5. Phobos, HiRISE. Long parallel grooves and chains of pits; Stickney at the right. Credit: NASA/JPL-Caltech/University of Arizona (PIA10368).

K.2 The contraction wrinkles

Phobos left hot, full of gas and expanded. In space it cooled from the outside in: its shell hardened first, and the interior went on shrinking beneath it. A rock cooled by

1,000 K contracts by about 3% in length ($\alpha \approx 3 \times 10^{-5} \text{ K}^{-1}$), a hundred times more than rock can stretch before it breaks; the shell had to crack and wrinkle, as the skin of a baked apple or a raisin does. The chains of pits that run along the grooves are read here as these wrinkles and collapses, not as impact craters.

K.3 Wrinkles are not craters

The difference shows on the surface. An impact crater that lands on a groove cuts it: the crater is younger, and it erases the part of the groove it falls on. Such craters exist on Phobos, superposed on grooves, and they interrupt them. The chains of pits do the opposite: they run along the grooves, merge into them and never cross them. Had they been impacts they would have erased grooves wherever they fell; instead they belong to the grooves. They are part of the same structure — wrinkles and collapses of a shrinking shell — not a later rain from outside. Beside them Phobos carries true impacts: old, worn hollows from the time of the ring, small craters made by material moving in the ring, and sharp craters made after it had gone. Hollows lie on hollows, which a wrinkle never does. The distinction is between two products, not a claim that there are no craters. The largest impact is Stickney, 9 km across on the leading side: a solid body, already moving in the ring before Phobos left, met head-on by a Phobos that was still warm. An impactor of 1.5–2 km at about 1 km s^{-1} suffices; it slowed Phobos by about 1 m s^{-1} , and played no part in keeping it inside the line.

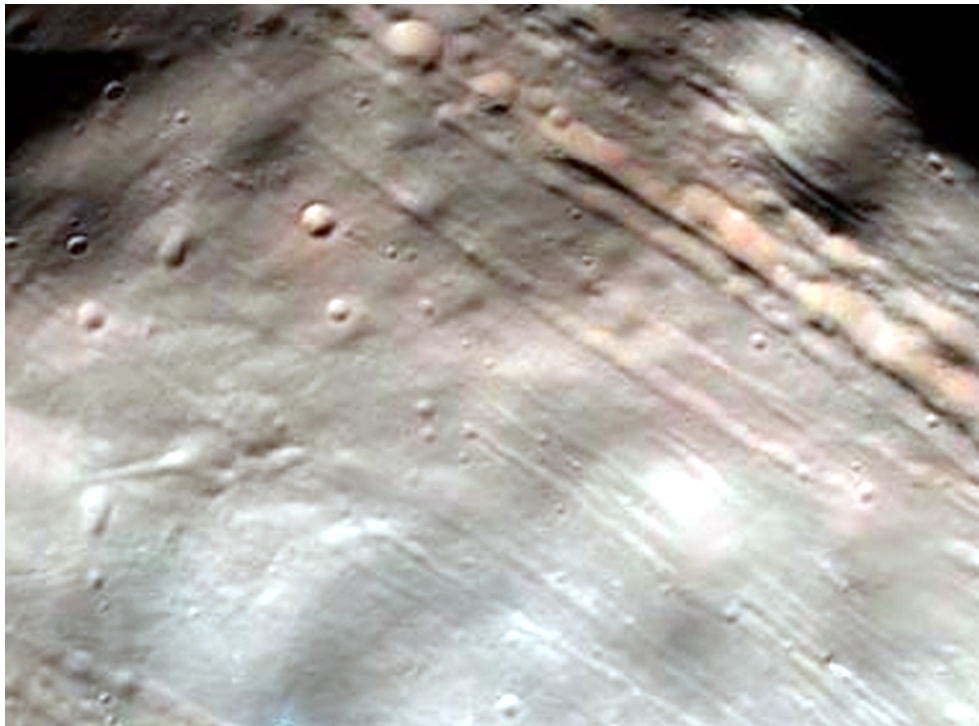


Figure 6. Phobos, HiRISE detail. Centre: small impact craters superposed on grooves, cutting them. Upper right: chains of pits running along the grooves and merging into them --- part of the groove, not later than it. Credit: NASA/JPL-Caltech/University of Arizona (HiRISE, detail).

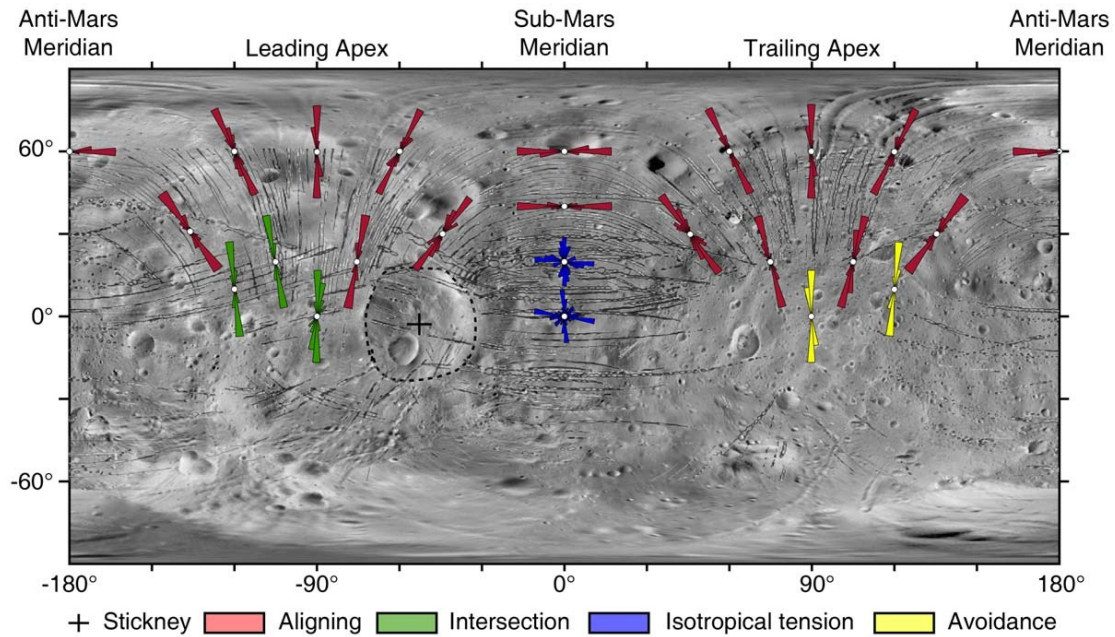


Figure 7. Groove orientations on Phobos as mapped by Cheng et al. (2022). The grooves form a few large, coherent families across the whole body. Credit: Cheng, Asphaug, Ballouz, Yu & Baoyin (2022), *Planet. Sci. J.* 3, 249, CC BY 4.0.

K.4 The orbit of a body that began to return

Phobos goes round Mars in 7.65 hours, 3.2 times in each Martian day, at 2.14 km s^{-1} ; its orbit is nearly circular (0.015) and within about a degree of the equator. Inside the corotation line, every body goes round faster than the planet turns; the tide it raises lags behind it and holds it back, and it spirals down. That is what Phobos is doing, and what it has done since the moving line caught it, at about 19,000 km (§G.3). The back-integration below does not depend on how Phobos reached that height; it fixes only where it stood when its fall began.

Fall began	Distance then	Its orbital period then
3.5 billion years ago	18,807 km	21.8 h
3.9 billion years ago	19,119 km	22.3 h
4.5 billion years ago	19,541 km	23.0 h
Today	9,375 km	7.65 h

Table 6. Phobos run backwards with the tidal friction measured for Mars today ($k_2/Q = 1.816 \times 10^{-3}$). In every case it began within a few per cent of the corotation line of a slowed Mars and has fallen since.

K.5 Why Phobos now goes round 3.2 times in a Martian day

When its fall began, Phobos and Mars were nearly in step: at about 19,100 km Phobos went round once in 22.3 hours, and Mars turned once in about 22 hours — close to one orbit per Martian day. The ratio of 3.2 seen today was built afterwards, by two changes acting in the same direction.

Phobos fell, and falling made it faster. A moon's speed is set by its distance: the closer, the faster. The tide holds Phobos back and takes energy from it, and it sinks; as it sinks it speeds up, from about 1.50 km s^{-1} at 19,100 km to 2.14 km s^{-1} at 9,375 km. Its period shortened from 22.3 to 7.65 hours — a factor of 2.9.

Mars slowed. The planet went on losing spin with the material and gas that left it through the corotation line, the ring among them: a ring outside the line carries away the spin it holds, and when it was gone that spin did not return. The Martian day lengthened from about 22 to 24.6 hours — a factor of 1.1.

	When the fall began	Today	Change
Distance of Phobos	19,100 km	9,375 km	
Speed of Phobos	1.50 km s^{-1}	2.14 km s^{-1}	
Period of Phobos	22.3 h	7.65 h	faster $\times 2.9$ (the fall)
Martian day	$\approx 22 \text{ h}$	24.6 h	slower $\times 1.1$ (Mars)
Orbits per Martian day	≈ 1	3.2	$2.9 \times 1.1 \approx 3.2$

Table 7. From one orbit per day to 3.2. Phobos began nearly in step with Mars; its fall and the slowing of Mars together produced the ratio seen today. The colour shows the growing difference between the moon and the planet.

L The traces of the ring

- **Two equatorial orbits.** Both moons lie within two degrees of the equatorial plane and on nearly circular orbits. A ring in the equatorial plane draws a body crossing it into that plane and rounds its orbit.
- **A face that follows time and place in the ring.** The body that stayed long in the ring is smooth, rounded and on the more perfect circle (0.0003); the body that met only its thin edge is grooved, roughened by gas rather than smoothed, and kept a small eccentricity (0.015).
- **The inclination of Deimos.** The ring left Deimos on a circle in the equatorial plane; its present tilt of about 1.8° was added later, by a resonance with an inner moon, and has itself been read in the accepted literature as the trace of a past ring of Mars (Ćuk et al. 2020). Independent work thus already places a ring around the young Mars.
- **Worn hollows.** The depressions of Deimos are three times shallower than those of Phobos (§J.1), and both moons carry an old generation of worn, rounded hollows beneath a young generation of sharp craters. Struck while still warm and plastic, a moon is not dug into a bowl but folded inward: low-speed contact with bodies moving almost in step leaves broad, shallow hollows. Only a moon that passed through a ring carries them. They were made early, at 7,500–15,000 km, so the near ring held solid bodies — rock and ice thrown from the volcanoes, which survive well inside the 13,000-km limit for loose ice (a solid ice block to about 7,700 km, rock to about 5,300 km). The grinding in the clumpy outer ring came later, and the sharp craters last, on bodies that had hardened.
- **A sharp end and a blunt end.** On the shape models of Ernst et al. (2023) each moon has one sharp end and one blunt end along its long axis: one kilometre

behind the tip, the section is 2.8 km in radius at the sharp end of Phobos against 4.7 km at its blunt end, and 2.4 against 2.9 km on Deimos. An erodible body in a flow is worn to a point facing the flow (Ristroph et al. 2012); in the ring the flow came from behind. The tide later locked each moon with its long axis toward Mars and its blunt, heavier end facing the planet, as the heavier near side of our Moon faces the Earth; today the sharp ends point away from Mars (prediction N.5).

- **Ages.** Crater counts put the surface of Phobos at about 4.3 billion years in a Mars-orbit chronology, or 3.5 in an asteroid-belt chronology (Schmedemann et al. 2014); the surfaces of both moons are near saturation and of similar crater density. The account expects Deimos to be the older.

M The water

- **Water that left.** Heavy hydrogen enriched six to seven times relative to the Earth's oceans, and an early water layer of at least 137 m (Villanueva et al. 2015): the record of the ring and of the steam that went to space.
- **Water that stayed.** A water-saturated mid-crust between 11.5 and 20 km depth beneath InSight, equivalent to a global layer 1-2 km deep (Wright, Manga & Pan-ning 2024): the water that never found the conduits and stayed sealed beneath the crust. The moons, soft when they were struck, show that the ground beneath the young surface was soft and soaked with water; the mid-crust of today is what remains of it.
- **One sealed crust.** The same impermeable crust that held the gas until the plugs moved is the crust that holds the water today.

The predictions

Each prediction gives what is expected, its value where one can be given, the instrument or data that will measure it, when, and what the accepted explanation expects at the same place — so that each measurement separates the two.

N The predictions

Prediction	Expected (this paper)	Measured by	When	Accepted explanation expects
N.1 Phobos material	Martian crust altered by water: oxygen, chromium and titanium isotopes on the Martian line; no impactor component; zinc and potassium isotopes not shifted by evaporation; hydrated minerals; closed vesicles of a cooled foam	MMX samples, ≥ 10 g of regolith	Return 2031	Impact disc: a mixture of Mars and impactor, much of it melted and re-condensed. Capture: primitive asteroid material

Prediction	Expected (this paper)	Measured by	When	Accepted explanation expects
N.2 Phobos grooves	Grooves and pit chains are one structure: pits never cross grooves; the grooves concentrated on the side that faced west in the conduit; groove walls narrow downward (V-shaped tension cracks); a surface etched and roughened by gas-borne dust, not smoothed: groove rims sharp or only slightly worn, unlike the rounded surface of Deimos	MMX imaging; future radar sounding	2027 on	Tides or Stickney ejecta; pit chains as secondary impacts
N.3 Deimos surface	Shallow, worn hollows (median depth about 2% of width, against 5.5% on Phobos); low ridges that are the roots of the tallest wrinkles; same composition as Phobos	MMX flybys of Deimos	After 2027	Accreted rubble; smoothness from regolith infill
N.4 Pavonis caldera	The deepest caldera for its width of the four (depth/width ≈ 0.10); a mass deficit beneath it	MOLA topography; gravity models	Now	An ordinary summit caldera of a shield volcano
N.5 The two moons	The same Martian material in both, Deimos the wetter (lighter); the centre of mass of Phobos displaced toward Mars, toward its blunt end	MMX samples, flybys and gravity field	2027–2031	Different histories; no prediction for the centre of mass
N.6 Water beneath Tharsis	A water-saturated mid-crust beneath Tharsis as beneath InSight	Future seismic stations	Future	No link between moons and buried water

Prediction	Expected (this paper)	Measured by	When	Accepted explanation expects
N.7 Martian dust	A component older than 4 billion years, of the composition of the Phobos regolith, with grains that carry solar-wind helium and neon; most abundant in the broad equatorial band and the dust continents (Tharsis, Arabia Terra, Elysium), mixed with rock ground by drought and wind	Returned Perseverance regolith samples; MMX	2031 on	Dust from weathering of rock alone; no separate ancient component

Table 8. Predictions, measurements and dates. MMX launches in October 2026, lands on Phobos in 2027 and returns its samples in 2031, with several flybys of Deimos (JAXA; Kuramoto et al. 2022). The full list of proposed measurements, mission by mission, is in Appendix B.

0 What the account requires

1. **A fast, expanded young Mars:** about 1.5 times today's radius and a 5-hour day. The planet then held about 12 times today's spin and must have lost about 92% of it, mostly with volatiles leaving through the corotation line — of order 5–20% of the starting mass (§H.3).
2. **A soft young Mars:** dissipating 8 to 20 times more than today for half a billion to a billion years, so that the tide carried Deimos from the ring at about 10,000 km to 23,463 km, past 20,428 km before Mars slowed to today's day (§G.2).
3. **The gas push:** a Pavonis about 30 km high, a conduit drilled through its height by steam and rock fragments, a soft, warm plug that seals it at its base, and trapped gas at 0.5–0.9 GPa driving the plug up the conduit in less than a minute, with a gas mass about that of the plug. The walls must hold that pressure for that time, three to five times what the surrounding rock presses back with; the cold, thick crust, the sealing plug and the short duration must close the gap (§C). This is the critical step of the account.
4. **The atmosphere and the ring:** a dense steam atmosphere turning with Mars below the corotation line, which carries the rising plug round with it (§E.2); and above the line a ring built by Mars from its own steam in its first stages, standing in the equatorial plane at the height of the moons' first paths when they were fired, massive enough to give each body the sideways speed it still lacks — from 0.03 to about 0.56 of its mass in perfect coupling, several times more in practice (§F). The account stands or falls with the ring: without it a plug fired from the surface falls back.
5. **The timing:** Deimos fired first, while the ring was dense and the line close to

the ground; Phobos fired later, braked and weaker, into the thin edge of a waning ring, while the line still lay below it. The tide pushed it outward, but the line moved outward faster and caught it near 19,000 km, when the day was about 22 hours (§G.3).

6. **The colour:** the dark, primitive-looking spectra of both moons must arise from Martian material altered by water and long exposure in space.
7. A focused study may give approximate numbers somewhat different from those of this paper; the sequence does not depend on their exact values.

Reproduction of the numbers

Every number of this paper is printed by the script `mars2_numbers.py` (Python 3, standard library only), kept with the files of this paper. Inputs: $GM = 42,828 \text{ km}^3 \text{ s}^{-2}$; today's radius 3,389.5 km, day 24.6229 h, inertia coefficient 0.3644; young radius $1.5 \times$ today, day 5 h, homogeneous ($k = 0.4$); Pavonis 30 km high, conduit 20–40 km; plugs of Deimos 14 km long at $1,200 \text{ kg m}^{-3}$ and of Phobos 18 km long at $1,600 \text{ kg m}^{-3}$; Phobos 9,375 km, $5,740 \text{ km}^3$; Deimos 23,463 km, radius 6.2 km; Pavonis caldera 47 km wide, 4.8–5.0 km deep; tidal friction $k_2/Q = 1.816 \times 10^{-3}$ today. The outward migration of each moon beyond the line integrates $da/dt = 3(k_2/Q)(m/M)(R/a)^5 na$ with the radius of the young Mars and a dissipation 8–20 times today's; the depth-to-width ratios of §J.1 are measured on the shape models of Ernst et al. (2023) at 36 m (Phobos) and 41 m (Deimos), with the same detection for both. The launch speeds solve energy and angular momentum for an equatorial launch from the summit with the free sideways speed of the ground, in free flight and, as the other bound, for a plug held in rotation by the atmosphere up to the line; the conduit pressures use $\bar{p} = \rho_p v^2 L_p / 2L_b + \rho_p g_{\text{eff}} L_p$; the wall holds about twice the surrounding rock pressure plus the strength of the rock; the gas-gun limit is $2c_0/(\gamma - 1)$; the spin removed through the line integrates $dL = \omega r_{\text{co}}^2 dm$ backwards from today.

APPENDIX B

Proposed measurements for MMX and other missions

The predictions of this paper can be tested with measurements that current and planned missions are designed to make. We list them by mission, so that each team can see what the account asks of its data. Each row gives what to measure, what the account expects, the result that would refute it, and what the accepted explanation expects.

#	Measure	Expected here	Refuted by	Accepted explanation
MMX (JAXA): Phobos landing 2027, sample return 2031, Deimos flybys				
B1	O, Cr and Ti isotopes; D/H of Phobos samples	On the Martian line	Primitive asteroid values	Capture: asteroid. Impact: Mars plus impactor
B2	Foreign component	None: pure Mars	A significant impactor component	Impact: a large one
B3	Zn and K isotopes	Unshifted: no evaporation and re-condensation	Light isotopes depleted	Impact: depleted
B4	Grain texture	Cooled volcanic foam: closed vesicles, hydrated minerals	Vapour-condensed glass spherules	Impact: melted and re-condensed
B5	Gravity field of Phobos	Centre of mass displaced toward Mars, toward the blunt end	Displaced toward the sharp end	No prediction
B6	Imaging of the grooves	Pit chains along grooves, never crossing them; grooves concentrated on one side; rims sharp or slightly worn; surface etched, not smoothed	Pit chains crossing grooves at random	Tides or Stickney ejecta

#	Measure	Expected here	Refuted by	Accepted explanation
B7	Deimos flybys: shape and hollows	Shallow, worn hollows; a sharp end and a blunt end, the blunt end toward Mars; composition as Phobos	A composition unlike Phobos	Accreted rubble; regolith infill
Mars orbiters (MRO, Mars Express, TGO)				
B8	Images east of each of the four Tharsis volcanoes, along their latitude	Chains of large blocks or craters: shots that fell back	—	No link to the volcanoes
B9	Gravity beneath the Pavonis caldera	A mass deficit: a chamber that fired	A mass excess	An ordinary shield caldera
Returned regolith samples of Perseverance				
B10	Age of single dust grains	A component older than 4 billion years, mixed with locally ground rock	—	Weathered rock alone
B11	Solar-wind He and Ne in the grains	Ancient grains that carry them, from their time in space in the ring	No such grains	No such grains
B12	Composition of the ancient component	As the Phobos regolith	Unlike it	No prediction
Future seismic stations				
B13	Mid-crust beneath Tharsis	Water-saturated, as beneath InSight	Dry	No link to the moons
A future mission				
B14	A sample of Deimos	The same Martian fingerprint as Phobos	A different origin	Unrelated histories

Table B1. Proposed measurements, mission by mission.

References

- Basilevsky, A. T., Lorenz, C. A., Shingareva, T. V., Head, J. W., Ramsley, K. R., & Zubarev, A. E. (2014). The surface geology and geomorphology of Phobos. *Planetary and Space Science*, 102, 95–118.
- Canup, R., & Salmon, J. (2018). Origin of Phobos and Deimos by the impact of a Vesta-to-Ceres sized body with Mars. *Science Advances*, 4, eaar6887.
- Clarke, A. B., Esposti Ongaro, T., & Belousov, A. (2015). Vulcanian eruptions. In H. Sigurdsson et al. (Eds.), *The Encyclopedia of Volcanoes* (2nd ed., pp. 505–518).

Academic Press.

Cheng, B., Asphaug, E., Ballouz, R.-L., Yu, Y., & Baoyin, H. (2022). Numerical simulations of drainage grooves in response to extensional fracturing: testing the Phobos groove formation model. *The Planetary Science Journal*, 3, 249.

Ćuk, M., Minton, D. A., Pouplin, J. L. L., & Wishard, C. (2020). Evidence for a past Martian ring from the orbital inclination of Deimos. *The Astrophysical Journal Letters*, 896, L28.

Ernst, C. M., Daly, R. T., Gaskell, R. W., et al. (2023). High-resolution shape models of Phobos and Deimos from stereophotoclinometry. *Earth, Planets and Space*, 75, 103.

Hesselbrock, A. J., & Minton, D. A. (2017). An ongoing satellite-ring cycle of Mars and the origins of Phobos and Deimos. *Nature Geoscience*, 10, 266–269.

Hurford, T. A., Asphaug, E., Spitale, J. N., et al. (2016). Tidal disruption of Phobos as the cause of surface fractures. *Journal of Geophysical Research: Planets*, 121, 1054–1065.

Hyodo, R., Genda, H., Charnoz, S., & Rosenblatt, P. (2017). On the impact origin of Phobos and Deimos I: thermodynamic and physical aspects. *The Astrophysical Journal*, 845, 125.

IAU Working Group for Planetary System Nomenclature / USGS Astrogeology Science Center. *Gazetteer of Planetary Nomenclature*, entry “Pavonis Mons”. <https://planetarynames.wr.usgs.gov/>.

JAXA. *Martian Moons eXploration (MMX)*, mission overview and schedule. <https://www.mmx.jaxa.jp/en/>.

Kuramoto, K., Kawakatsu, Y., Fujimoto, M., et al. (2022). Martian Moons Exploration MMX: sample return mission to Phobos elucidating formation processes of habitable planets. *Earth, Planets and Space*, 74, 12.

Murray, J. B., & Heggie, D. C. (2014). Character and origin of Phobos’ grooves. *Planetary and Space Science*, 102, 119–143.

NASA/JPL Solar System Dynamics. *Planetary Satellite Physical Parameters*. https://ssd.jpl.nasa.gov/sats/phys_par/.

Ojha, L., Lewis, K., Karunatillake, S., & Schmidt, M. (2018). The Medusae Fossae Formation as the single largest source of dust on Mars. *Nature Communications*, 9, 2867.

Pätzold, M., Andert, T. P., Cardesín-Moinelo, A., Cicchetti, A., & Ziese, R. (2025). Investigations of the Moon Phobos by Mars Express and implications towards its origin. *Space Science Reviews*, 221, 41.

Ramsley, K. R., & Head, J. W. (2019). Origin of Phobos grooves: testing the Stickney crater ejecta model. *Planetary and Space Science*, 165, 137–147.

Ristroph, L., Moore, M. N. J., Childress, S., Shelley, M. J., & Zhang, J. (2012). Sculpting of an erodible body by flowing water. *Proceedings of the National Academy of Sciences*, 109, 19606–19609.

Rosenblatt, P., Charnoz, S., Dunseath, K. M., et al. (2016). Accretion of Phobos and Deimos in an extended debris disc stirred by transient moons. *Nature Geoscience*, 9, 581–583.

Schmedemann, N., Michael, G. G., Ivanov, B. A., Murray, J. B., & Neukum, G. (2014). The age of Phobos and its largest crater, Stickney. *Planetary and Space Science*, 102, 152–163.

Thomas, P. (1979). Surface features of Phobos and Deimos. *Icarus*, 40, 223–243.

Thomas, P., Veverka, J., Bloom, A., & Duxbury, T. (1979). Grooves on Phobos: their distribution, morphology and possible origin. *Journal of Geophysical Research*, 84, 8457–8477.

Villanueva, G. L., Mumma, M. J., Novak, R. E., et al. (2015). Strong water isotopic anomalies in the martian atmosphere: probing current and ancient reservoirs. *Science*, 348, 218–221.

Wright, V., Manga, M., & Panning, M. P. (2024). Liquid water in the Martian mid-crust. *Proceedings of the National Academy of Sciences*, 121, e2409983121.

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