

larger volume of the universe—than it otherwise could. But that improvement is only the beginning.

“This is now the baseline for any future upgrade,” says Barsotti. Before, LIGO had to deliberately throttle its light-squeezing efforts to avoid compromising its low-frequency sensitivity, but that’s no longer the case. “The next step

is to improve how much squeezing we can see,” Barsotti explains. “We can squeeze the light as much as we want, and we’re only limited by how well we can get it into the interferometer. This is going to be important not only for LIGO but for all future ground-based gravitational-wave detectors.”

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Uncovering the molten mantle of Mars

A delay in seismic-wave arrival times reveals the presence of an additional layer in the planet’s interior.

Mars is only the second celestial body, after the Moon, that humans have sent seismometers to. A desire to

understand its interior, which holds clues to Mars’s origin and evolution, motivated NASA to develop *InSight* (*Interior Exploration Using Seismic Investigations, Geodesy and Heat Transport*). Before that mission, astronomers’ knowledge of Mars’s interior came primarily from models of solar-system formation, Mar-

tian meteorites, and geophysical observations from satellites orbiting the planet. Those data provided only an incomplete glimpse of Mars’s interior.

The seismometer on the *InSight* lander—known as SEIS, or the Seismic Experiment for Interior Structure—collected data from 2019 to 2022 by listening

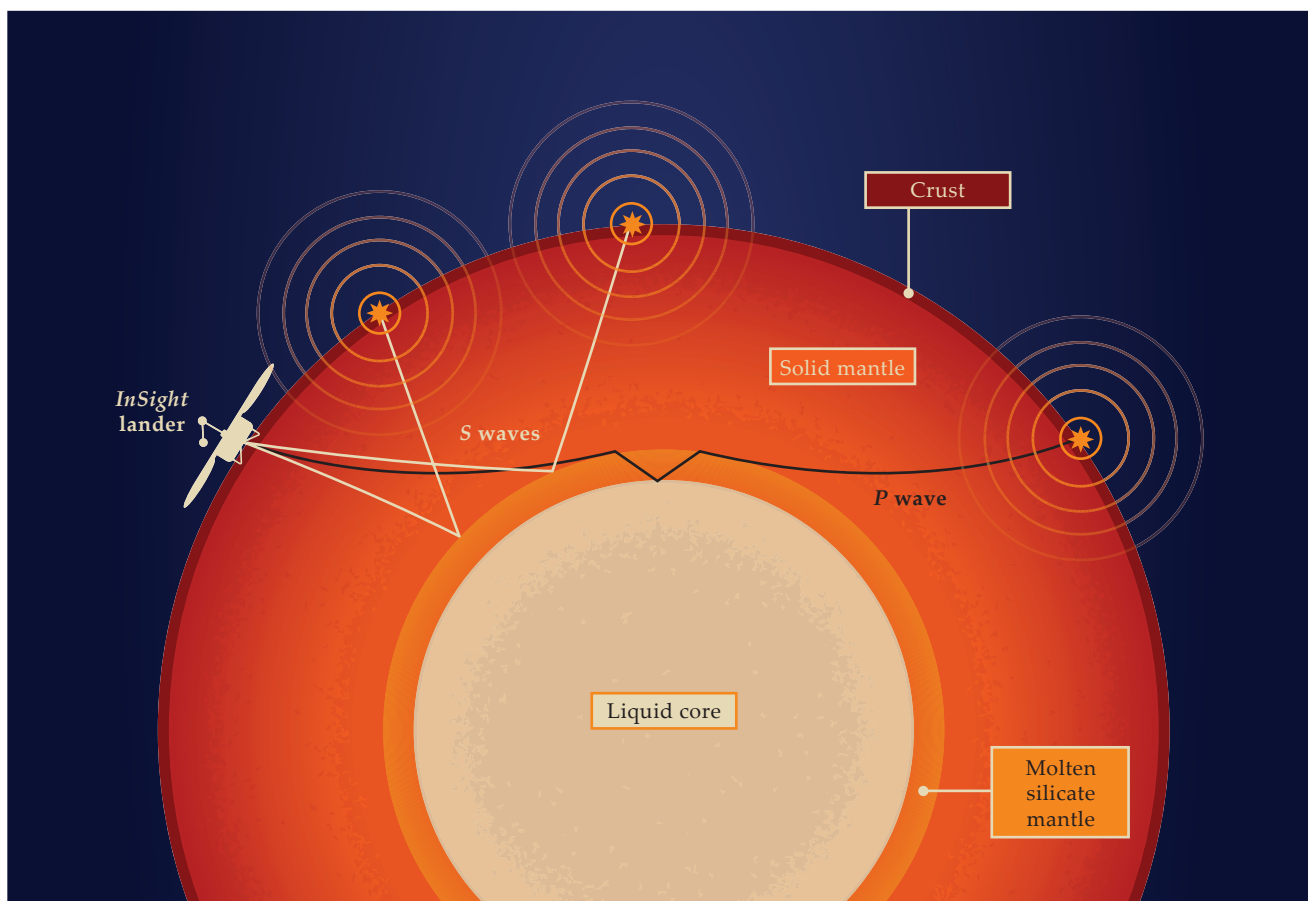


FIGURE 1. MARS’S INTERIOR STRUCTURE can be inferred from seismic waves that travel through the planet. Waves go out in all directions from the seismic events; shown here are examples of wave paths that support the existence of a deep liquid silicate mantle layer just above the core. S waves from events near the *InSight* lander reflect off the solid–molten boundary and can be used to determine the inner radius of the solid mantle. An event farther away allows the seismometer to detect P waves that penetrate to deep layers of the planet, revealing the presence of a molten silicate mantle layer. (Adapted by Jason Keisling from ref. 1.)

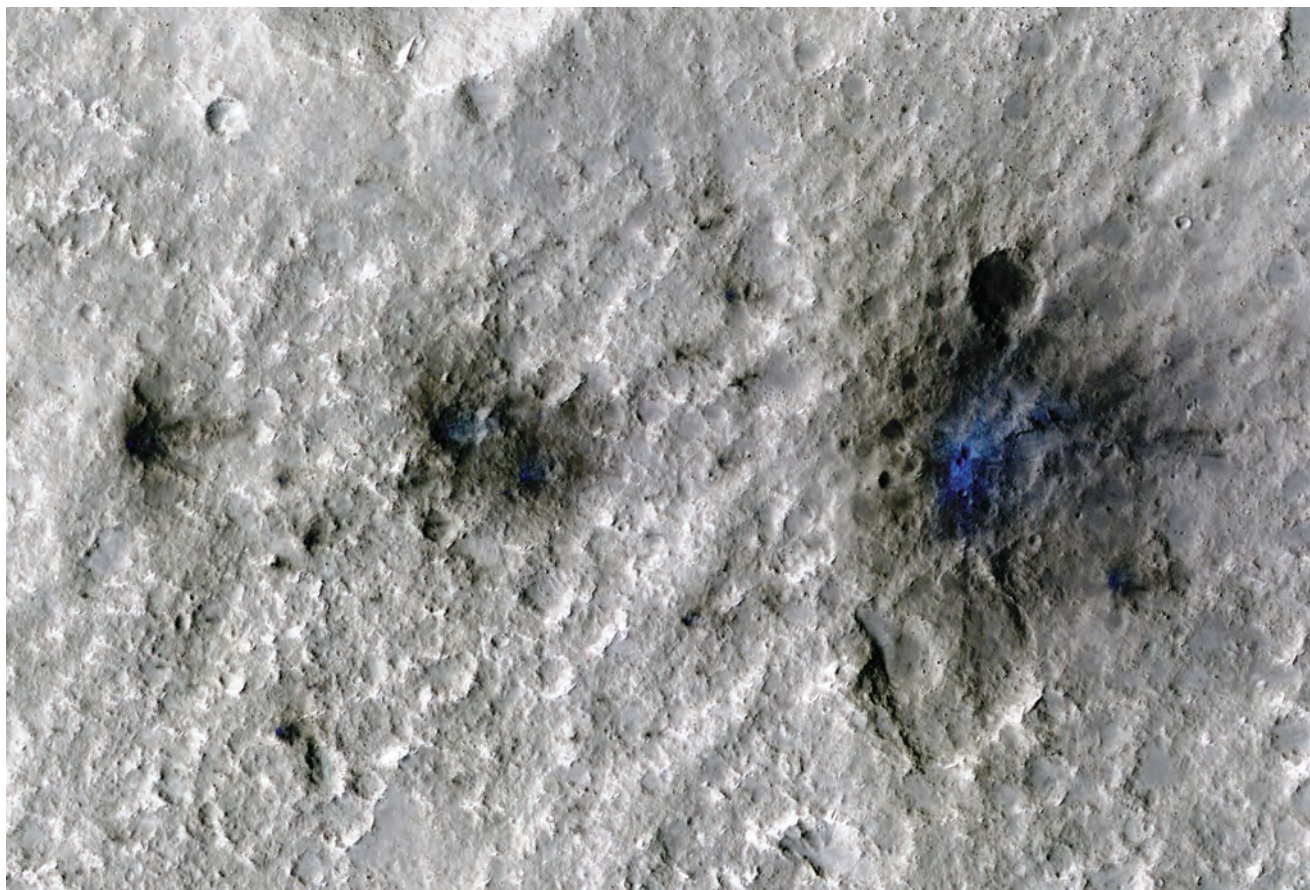


FIGURE 2. A METEORITE IMPACT on Mars on 5 September 2021 produced seismic waves detected by NASA's *InSight* lander on the other side of the planet. NASA's *Mars Reconnaissance Orbiter* then took this image of the impact location. The blue was added to highlight where the soil was disturbed. (Courtesy of NASA/JPL-Caltech/University of Arizona.)

to marsquakes and other tremors caused by meteorites landing on Mars's surface. (For more on *InSight*, see *PHYSICS TODAY*, October 2021, page 17.) Because SEIS is the only seismometer on the planet, observations can't be as precise as those from the network of seismometers on Earth, but one is better than none. Now scientists have direct data from Mars that challenge the previous two-layer (mantle and core) interior model.

In fact, the existing interior models have had to be updated following the analysis of a rare impact late in the third year of *InSight*'s data collection. Seismic waves from a meteorite strike on the far side of the planet traveled deep into the mantle and reached SEIS later than expected (see figure 1). In October 2023 two independent research teams, led by Henri Samuel and Amir Khan, used the data from the event to conclude that Mars's mantle isn't homogenous: It is stratified into silicate layers with distinct compositions and states of mat-

ter—that is, the mantle is divided into solid and molten layers. Those layers create boundaries in the seismic properties—density and seismic wave speeds—that alter the path of seismic waves traveling through the planet. Each team used different methods to reach the same conclusion,^{1,2} lending credibility to the existence of a molten mantle layer.

Identifying anomalies

Samuel, a CNRS research scientist at the Paris Institute of Planetary Physics and Paris Cité University, joined the *InSight* team in 2017, before the May 2018 launch. He had been looking at Mars from a geodynamics perspective. Existing models of the planet's interior structure, which assumed a homogeneous mantle in the present day, didn't match his understanding of its formation. During its early formation, Mars, like Earth, was enveloped in a magma ocean. Metals and silicates then separated,

with the heavier metals sinking into the core and the lighter silicates rising to form the mantle layer. When the planet cooled, the different components in the solidifying silicate magma ocean would have stratified because they had different solubilities in solid or liquid silicate phases.

Based on that stratification of different materials, Samuel and his collaborators expected Mars to have a heterogeneous interior mantle, not a homogeneous one. But existing models assumed that present-day Mars had settled into a homogeneous mantle. "I didn't see any reason for that," Samuel says. "So I wanted to explore these other possibilities." In early 2021 Samuel and colleagues proposed that the Martian mantle had a bottom molten layer that hadn't cooled to a solid, and they made predictions about which observations would support that conclusion.³ The researchers hoped that the *InSight* mission would allow them to investigate the interior structure and test the hypothesis.

But the early data from *InSight* weren't sufficient to test the idea. For most of the mission, the SEIS instrument was detecting only events near it, and quiet ones at that. Samuel needed seismic waves originating far from *InSight*. Only those waves would penetrate deep enough to traverse the deepest regions of the mantle, where a liquid layer would be, on their way to the seismometer.

Khan, a senior scientist at the Institute of Geochemistry and Petrology at ETH Zürich, focuses on understanding the Martian interior from a combined seismic, mineral-physics, and cosmochemical standpoint. He has been working on the *InSight* team since 2013. In 2021 he coauthored a series of papers based on the *InSight* data obtained to date.⁴ Among the results was the calculated average density of the core—based on the volume of the core and the total mass of Mars—which turned out to be surprisingly low.

But the volume was derived from seismic waves that had reflected off an internal solid–liquid boundary deep within the planet. The reflected waves could provide only the radius of what the majority of the *InSight* team, at the time, assumed to be the core. “That’s what limited our point of view back then,” Khan says. To understand the properties of what was within the assumed core radius, he also needed data from seismic waves traveling through that region.

Existing data and models indicated that Mars’s core, similar to Earth’s, was primarily iron and nickel. The results for the core’s average density, however, implied that it contained an unexpectedly high abundance of light elements—chiefly sulfur, carbon, oxygen, and hydrogen. That didn’t make sense to Khan and his collaborators for two reasons. First, the meteorites from which the early terrestrial planets are thought to be made up didn’t have the requisite elemental distribution: They didn’t contain enough light elements. Second, even if those elements were present in sufficient abundance, only a fraction would sink to the core alongside the heavy metal elements; the rest would remain in the silicate mantle.

Fateful impact

Like seismometers on Earth, the SEIS instrument was used to measure two types of waves that pass through the

planet’s interior. *S* waves are transverse waves that travel only through solids; they reflect off a solid–liquid boundary and can be used to determine the depth of the boundary between the solid mantle and the adjacent liquid layer. *P* waves are faster longitudinal waves, which travel through both solids and liquids.

The difference in arrival times between the two wave types helps researchers pinpoint the location of a marsquake. And for the majority of the mission, the determination of the interior structure of Mars was limited because the seismic events were mostly nearby. But both teams were hoping for diffracted and core-transiting *P* waves coming from the far side of the planet, as depicted in the diagram in figure 1. Waves that traveled past the solid–liquid boundary could support Samuel’s heterogeneous hypothesis and provide an answer to the density discrepancy seen by Khan.

In September 2021, on the 1000th Martian day after *InSight* landed, three fragments of a meteor struck the far side of Mars. The impact was observed in two ways. *InSight* recorded both *S* and *P* waves with SEIS, and the exact site of the impact was also detected by NASA’s *Mars Reconnaissance Orbiter* (see figure 2), which provided precise location data most other seismic events lacked.

Because the location of the impact was known, the expected difference in arrival time between a *P* wave reflecting once underneath the surface of the planet and a *P* wave diffracted by the solid–liquid boundary could be determined with good accuracy. Using inversion analysis of the seismic data conducted by Mélanie Drilleau, an engineer at ISAE-SUPAÉRO, Samuel’s group concluded that the *P* waves moving through or tangential to the core traveled slower than predicted by a purely homogenous model of the interior. There had to be another layer whose seismic properties differed from those of the solid mantle and created an additional boundary that altered the path of the waves and slowed them down. Moreover, at least the largest part of the additional layer had to be at least fully liquid to explain the reflected *S* waves and to slow down the *P* waves.

Khan, meanwhile, reached out to his colleague Dongyang Huang, an experimental mineral physicist at ETH Zürich,

to determine from first principles the makeup of the new layer.⁵ Huang created models that simulate various seismic properties, such as the velocity of *P* waves, based on different elemental compositions of Mars’s core. Those models were then compared with real SEIS data to constrain the most likely scenario. Khan and colleagues found that the *P*-wave velocity and density of core materials were consistent with *InSight* observations if Mars has a molten layer at the base of the mantle. *S* waves were reflecting off the solid–liquid boundary within the mantle, as shown in figure 1, and not off the mantle–core boundary.

A new molten model

The *InSight* mission has ended, so with no other seismometers on Mars, it is difficult to verify the conclusion. Yet the fact that both groups determined that there is a molten silicate layer is reassuring. The immediate next step is reviewing previous Mars data from *InSight* and other probes in light of the new picture of the interior structure.

“This layer influences the entire evolution of the planet,” Samuel says. The presence of a molten layer would have reduced the core’s cooling rate while allowing the upper layers to cool faster, thus leading to a thin crust. The temperature evolution of the liquid core, in particular, would influence the generation and duration of Mars’s magnetic field. Understanding why the planet’s magnetic field weakened to the patchy field we see today is an active research topic among planetary scientists.

Samuel’s group further suggests that above the molten silicate layer is another, partly molten layer. The more complex structure would help explain other ongoing mysteries about Mars, such as how a planet with a thick, solid mantle is able to tidally deform in response to the orbit of its inner moon, Phobos.

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