laminates. The precise arrival time for each frequency component, which is essential for accurate velocity calculations, can be identified by locating the peaks of the wavelet transform magnitude within the time frequency plane. Group velocities for the flexural mode were recorded across several directions within the laminated specimens. Theoretical dispersion curves were generated using Mindlin plate theory, which provided high accuracy because it incorporates the critical effects of shear deformation and rotary inertia. By integrating the frequency dependent arrival times and the angular dependence of the group velocity, an accurate method for source localization was achieved for unidirectional and quasi isotropic laminates. These findings provide a dependable framework for the advanced diagnostics of composite structures.

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GENERAL FEATURES OF THE INTERNAL STRUCTURE OF THE PLANET MARS

Vidmachenko Anatoliy Petrovych
Doctor Phys.-Math. Sci., Professor,
Professor of Department of Physics
National University of Life and Environmental Sciences of Ukraine
Kyiv, Ukraine

Abstract. The Martian crust is the outer solid layer of the planet, mostly basaltic. It is rich in silicates, oxygen, iron, magnesium, etc. Estimates of the thickness of the crust vary from 10 to 47 km. Unlike Earth, which has moving lithospheric plates, the Martian crust is the only relatively immobile global plate. Beneath the crust is the mantle. It probably consists of a single thick layer, consisting mainly of silicate rocks rich in magnesium and iron. In the center of Mars is a metallic core with a radius of 1630-1860 km and a density of 6.2-6.3 g/cm^2. At least the outer part of the Martian core is in a liquid, molten state, and in the middle is a solid inner core.

Key words: Mars, internal structure, lithosphere, mantle, solid inner core.

Features of the structure of the layers of the internal structure of the planet Mars. The local structure of the upper part of the Martian soils (i.e., the outer layers of the planet's crust) was determined at the landing sites of numerous modules. It showed significant horizontal heterogeneity of these regions on the planet, and even the presence of frozen water [25, 26].

For example, the results of the "Mars Pathfinder" mission [22, 23] led to the conclusion that the processes that occurred on early Mars and on early Earth are significantly similar. For example, in terms of silica content, a significant proportion of materials in the Martian crust turned out to be similar to the continental part of the crust on Earth [5, 16, 25].

Crust. The Martian crust is the outer solid layer of the planet. Its composition is mainly basaltic, which is similar to the oceanic crust of the Earth and the lunar seas [3, 33], formed by impact events [7-9, 29]. It is rich in silicates, oxygen, iron, magnesium, aluminum, calcium, and potassium.

The characteristic red color of the Martian surface is due to the high content of iron oxides (rust) in the upper layers of the crust and in the regolith [2, 14, 15]. Some studies indicate the possible presence of more evolved rocks, similar to terrestrial andesites, or to quartz glass; this may indicate more complex geological processes in the past. It is also noted a significantly higher sulfur content (in the form of sulfates) compared to the Earth's crust.

One of the key results of the "InSight" mission was the refinement of the thickness of the Martian crust. It turned out that it, at least at the landing site of the device, is thinner than many previous models predicted. Thickness estimates from InSight data range from 10 km to 20 km (if there are two sublayers) or 37 km (if there are three sublayers).

Other analyses of seismic data [13] suggest models with an average thickness of 15–25 km (a "thin" two-layer model) to 27–47 km (a "thick" three-layer model). That is, the crust beneath the landing site consisted of three distinct inner sublayers. The upper crustal layer is estimated to be about 10 km deep, with denser, iron-rich layers extending further down to about 40 km below the surface.

These values contrast with older models that assumed an average thickness of about 50 km and a maximum of up to 130 km, although the thickness at the InSight landing site may be closer to 50 km. In comparison, the thickness of the Earth's crust is about 5–10 km under the oceans and 30–50 km under the continents. "InSight" data [10] also support the hypothesis of a possible multilayer structure of the Martian crust, which may consist of two or even three separate layers. The layering may reflect different episodes [17, 28, 30, 32, 36] of volcanic activity or different types of magma that participated in its formation.

Unlike Earth with its moving lithospheric plates, the Martian crust is a single, relatively stationary global plate. The lack of active plate tectonics [18] is a fundamental difference between Mars and Earth.

On Earth, plate motion continuously redistributes volcanic activity along plate boundaries. On Mars, mantle plumes (hot spots) remain stationary relative to the stationary Martian surface. This allows for the continuous eruption and accumulation of huge volumes of lava in one place over hundreds of millions of years, which directly explains the formation of colossal shield volcanoes such as Olympus Mons. In addition, the enormous weight of these concentrated volcanic loads, especially the Tharsis uplift, has caused planetary stresses that have led to the formation of radial faults and grabens. This establishes a direct causal relationship between the unique rigidity of the Martian crust and the scale and distribution of its major volcanic and tectonic features.

Mantle. Beneath the crust lies the mantle, a thick layer composed primarily of silicate rocks rich in magnesium and iron. Seismic data indicate that the upper Martian mantle exhibits a zone of low seismic wave velocities. The mantle appears rigid down to a depth of about 250 km, implying a very thick lithosphere compared to Earth. Below this rigid zone, the mantle gradually becomes more ductile, and seismic wave speeds begin to increase again.

A notable difference from Earth's interior is the apparent lack of a thermally insulating layer in the Martian mantle, similar to Earth's lower mantle. Instead, below a depth of about 1050 km, the mineralogy of the Martian mantle becomes similar to Earth's transition zone. The “InSight” probe has probed the upper mantle to depths of about 800 km. The Martian lithosphere, which includes both the crust and the rigid upper mantle, extends about 500 km below the surface, resting on a mantle that is relatively cold compared to Earth's.

The description of the Martian mantle as “rigid” to a depth of about 250 km, giving Mars a very thick lithosphere compared to Earth, is a critical discovery that directly confirms the planet's low level of tectonic activity. The thicker, more rigid lithosphere fundamentally hinders the energetic convective flow of the mantle that drives plate tectonics on Earth. This rigidity means that heat from the interior is not efficiently transported to the surface by plate reworking and subduction.

Consequently, the planet cools more slowly from its deep interior, and its surface remains relatively stable, preventing the formation of large mountain ranges or dynamic fault systems typical of Earth. This highlights the direct correlation between the physical properties of the mantle and the overall geological dynamism of the planet. The mantle extends from the lower boundary of the crust to the outer boundary of the core, and it is the primary driver of much of the tectonic and volcanic surface features on the planet. Estimates of the thickness of the mantle vary somewhat across sources, ranging from 1,240 to 1,880 km.

Unlike Earth, which has a distinct upper and lower mantle, the Martian mantle is likely to consist of a single layer. Some evidence suggests that the mantle may be partially molten, although its tectonic and volcanic activity is much lower than that of Earth's mantle, especially in the modern era. The lack of active plate tectonics on Mars is likely due to its smaller size, which has led to faster cooling compared to Earth, and to the formation of a thick, rigid lithosphere (which includes the crust and upper mantle) that cannot be easily broken into moving plates.

Core. Mars has a metallic core at its center. By analyzing the travel time of seismic waves, it is possible to determine the characteristics of the medium they traverse. The radius of the Martian core has been found to be between 1,780 and 1,810 km, and the density is 6.2-6.3 g/cm^2.

It was the data from the “InSight” mission that allowed us to significantly refine its size and properties. Models of the structure of Mars, supplemented by the collected data, indicate that the core of Mars is extremely large relative to the size of the planet itself. According to recent estimates, its radius is from 1630 km to 1860 km. Even the smaller of these values mean that the core radius is more than half the planet's radius; and this is a much larger relative fraction compared to Earth, where the core radius (~1221 km) is only about 19% of the planet's radius. The core consists mainly of iron (Fe) and nickel (Ni), but contains a significant admixture of lighter elements, which is estimated at about 20% of the mass of the core. The main light element is sulfur (S). Oxygen (O) and, possibly, carbon (C) and hydrogen (H) are also present there. The presence of these light elements makes the core of Mars less dense than if it consisted of a pure iron-nickel alloy. The presence of these light elements lowers the melting point of the core, which helps explain why it remains molten despite the planet's significant cooling since its formation.

Seismic data from the "InSight" spacecraft have confirmed that at least the outer part of Mars' core is in a liquid, molten state. The question of the existence of a solid inner core (Fig. 1), similar to Earth's, remains a subject of research. Some models suggest its existence, but direct seismic evidence is still lacking. An interesting discovery was the discovery of a possible layer of molten silicates about 150 km thick at the boundary between the mantle and the core. This layer may act as a thermal insulator, affecting the heat flow from the core and its evolution. The large size of the Martian core, its liquid state, and the high content of light elements, particularly sulfur, are key factors explaining the absence of a modern global magnetic field [1, 11, 24].

High sulfur content [21] is known to lower the melting point of iron, which may hinder the formation of a solid inner core or the efficient convection in the liquid core required to generate a magnetic field through the dynamo effect. An additional factor may be the recently discovered layer of molten silicates at the base of the mantle, which acts as a thermal insulator, inhibiting cooling and convection in the core. Without strong convection, the dynamo effect, which likely existed in early Mars history (as evidenced by residual magnetic fields in the crust), would have died out. The core temperature is estimated to be in the range of 2000–2400 K, which is significantly colder than the solid inner core of Earth (5400–6230 K). Although the InSight mission confirmed the liquid state of the core, the possibility of a solid inner core could not be definitively ruled out for geophysical reasons.

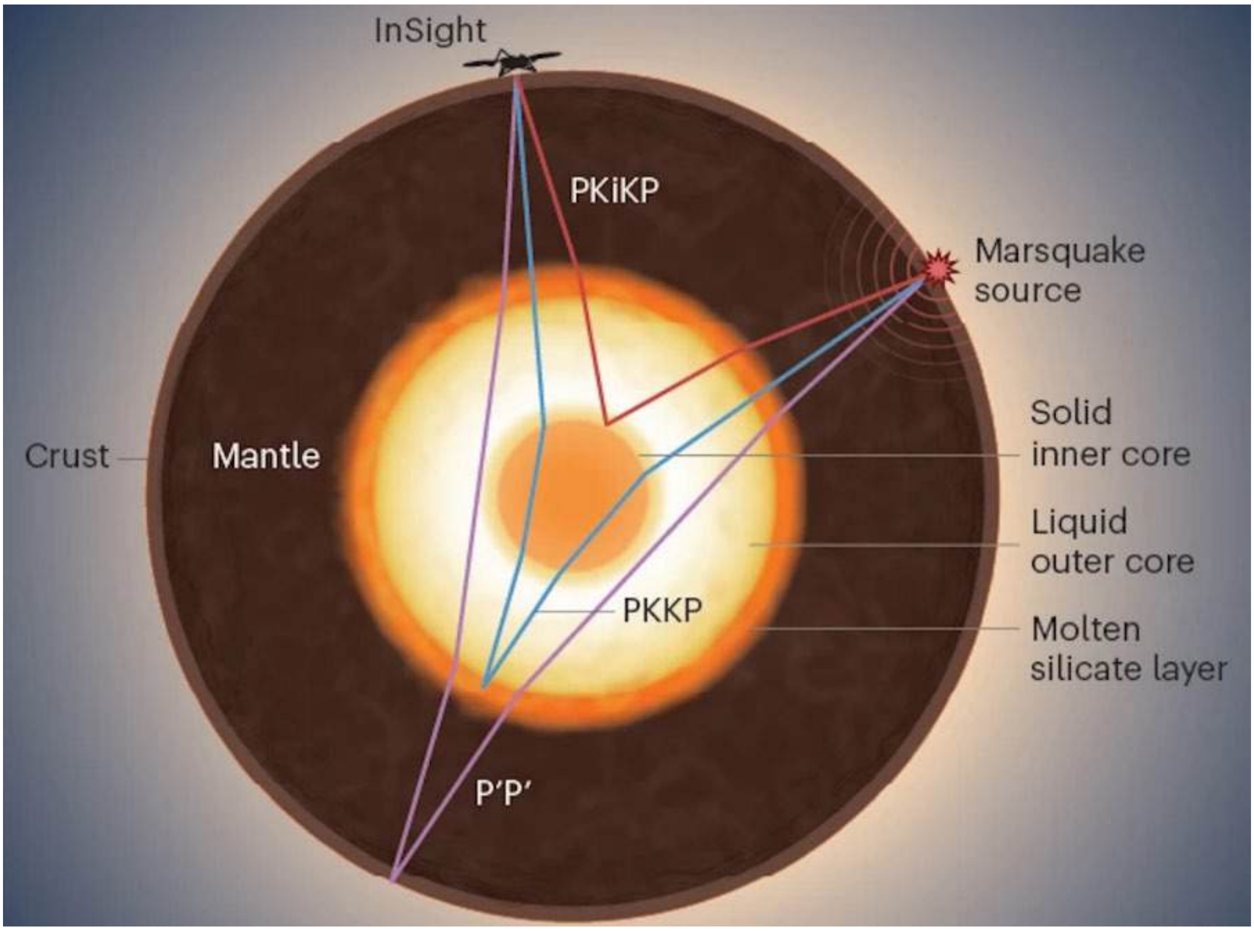

Figure 1. An illustration of how InSight helped reveal Mars' solid core by using seismic waves to travel through the planet [4].

Recent laboratory experiments at high pressures and temperatures suggest that Mars may have a solid inner core composed of an iron sulfide phase (Fe_4+xS_3) if temperatures in the center of the planet fall below about 1960 K, which is within the estimated range for the core. Sulfur, in particular, stands out as a likely major light element in the Martian core.

Martian quakes have helped determine the composition of the Martian core. The “InSight” lander has obtained new seismic data. The center of the Red Planet should contain a liquid alloy of iron and nickel, and about a fifth of its mass consists of light elements with a predominance of sulfur; there is also carbon, oxygen, and hydrogen. Thus, from 20 to 22 percent of the mass of the core may be low-melting elements, mostly sulfur, which coincides with ideas about the planetary structure. These results will help refine models of Mars' formation and evolution, including how conditions on the planet have changed [27, 34, 35].

The Martian core is therefore less dense than our own planet's core. This information will help us understand Mars' history and why it is now arid, with a dusty surface [12, 14, 31]. The composition of the Martian core and its largely molten state are central to better understanding the planet's past magnetic field. On Earth, convection in the liquid outer core generates a global magnetic field. Mars also once had a global magnetic field, remnants of which are “frozen” in its crustal rocks. The loss of this magnetic field, likely due to cooling and slowing of the core dynamo activity, would have had catastrophic consequences for atmospheric retention and surface habitability [19, 20], allowing the solar wind to strip away the atmosphere and increasing surface radiation.

Further geophysical observations are needed to confirm the existence, size, and density of the Martian inner core.

The debate over the presence of a solid inner core is still ongoing, as crystallization of the inner core affects the dynamics and longevity of convection in the liquid outer core; and therefore the potential for a possible dynamo. This directly links the thermal and compositional evolution of the deep interior to the long-term conditions in the planet's environment and its potential to support possible life forms.

For rocky terrestrial planets, the presence of a solid part of the inner core should significantly affect the composition and thermal evolution of their cores; the magnetic history of these planets is also affected. Geophysical observations on Mars have confirmed that the core of this planet is at least partially liquid. However, it remains unknown whether any part of the planet's core is solid.

Careful analysis of seismic data obtained by the “InSight” mission allows us to conclude that Mars does have a solid inner core [4]. The existence of an inner core is indicated by the observational data indicating two seismic reflection phases from the interior of the planet: a phase of deep transit through the core, and a phase of reflection at a certain boundary of the inner core.

Such inversions allow us to limit the radius of the inner core of Mars to approximately 613±67 km with a jump in the compression rate at the boundary of the inner core of almost 30%. This fact can be supported by additional seismic phases that should be associated with the inner core.

These properties mean the concentration of various light elements precisely in the inner core, which should be separated from the outer core due to the crystallization of certain parts of the core.

This discovery provided a certain starting point for a more complete understanding of the thermal conditions and chemical state in the interior of Mars. In addition, the connection between the processes of formation of the inner core itself and the evolution of changes in the magnetic field for Mars can provide an idea of the generation of dynamos on such planetary bodies.

Lithosphere and its features. Like Earth, Mars has a lithosphere, which is a rigid outer layer that includes both the crust and the upper part of the mantle (Table 1). A distinctive feature of Mars is its exceptionally thick lithosphere, which extends for about 500 km beneath the surface. This rigidity contrasts sharply with the more fragmented and dynamically active lithosphere of Earth. This thickness also contributes to Mars's much lower seismic activity compared to Earth. That is, the very thick lithosphere, compared to Earth, is a direct consequence of Mars' smaller size and its faster cooling compared to our planet.

The thick, rigid lithosphere means that mantle plumes [6], which are thought to be the source of Martian volcanism, are less likely to cause large-scale deformation of the crust, or to erupt in numerous, distributed locations. Instead, this rigid shell provides a stable, long-lasting conduit for repeated eruptions of magma at the same location on the surface.

Table 1 – Internal Structure of Mars: Parameters and Composition

Layer	**Thickness/Radius**	**Basic composition**	**Physical state: Key characteristics**
Crust	25-40 km (under “InSight”), average 42-56 km, maximum 117 km	Silicon, oxygen, iron, magnesium, aluminum, calcium, potassium; tholeiitic basalt	Three sublayers, single rigid plate (no plate tectonics)
Mantle	Extends from crust to 1560 km depth (total thickness ~1500 km)	Silicates	Rigid upper mantle (~250 km), ductile lower mantle, relatively cold compared to Earth
Core	Radius ~1830 km (larger than expected)	Iron, nickel, enriched in light elements (sulfur, oxygen, carbon, hydrogen)	Completely molten; less dense than expected; possibility of solid inner core (Fe_4+xS_3) under certain temperature conditions

This explains the formation of the huge single-source shield volcanoes observed in regions such as Tharsis, as volcanic material accumulates over geological timescales without being dispersed by plate motion.

This structural feature of the lithosphere is a key factor in the unique scale and morphology of Martian volcanic features.

Comparison of the internal structure of Mars and Earth. A comparison of the internal structure of Mars and Earth reveals both similarities and significant differences, reflecting their different masses, sizes, and evolutionary paths.

Similarities:

● Both planets have a differentiated structure: a metallic core, a silicate mantle, and an outer crust.

● The cores of both planets are predominantly iron.

● The mantles are composed of silicate rocks.

Differences:

● The core of Mars occupies a much larger fraction of the planet's volume (>50% of the radius) than the core of Earth (~19% of the radius).

● The core of Mars contains significantly more light elements ~(20÷22)%, mainly sulfur, compared to the Earth's core.

● The core of Mars is mostly liquid; the existence of a solid inner core is questionable; a molten silicate layer is possible at the core-mantle boundary. Earth has a well-defined solid inner core and a liquid outer core.

● The mantle of Mars is probably single-layered, while Earth has an upper and lower mantle.

● The crust of Mars is a single plate, while Earth's is broken into moving tectonic plates. The thickness of the Martian crust is variable and may be thicker on average than Earth's continental crust, although recent data indicate a slightly thinner crust in some regions.

● Plate tectonics is active on Earth, but practically absent on Mars.

Earth has a strong global magnetic field generated by the dynamo effect in the core. Mars today has no global field, only local residual magnetic anomalies in the crust. This table 2 summarizes the key differences in internal structure that explain the different geological activity and evolution of Mars and Earth.

Table 2 – Comparison of the internal structure of Mars and Earth

Layer	**Parameter**	**Mars**	**Earth**
Crust	Average thickness (km)	10-72 (variable, possibly multilayered)	~5-10 (oceanic), ~30-50 (continental)
	Major composition	Basalts, silicates (Fe, Mg, Al, Ca, K), iron oxides, sulfates	Basalts (ocean), granites/silicates (continent)
	Structure	Single slab, possibly 2-3 layers	Moving tectonic plates
Mantle	Thickness (km)	~1240 - 1880	~2900
	Major composition	Silicates (Mg, Fe)	Silicates (Mg, Fe)
	Structure	Probably single layer, partially molten (?)	Upper and lower mantle, convection
Core	Radius (km)	~1630 - 1860	~3485 (total), ~1221 (internal)
	% of planet radius	~48 - 55%	~55% (total), ~19% (internal)
	Major composition	Fe, Ni, ~20% light elements (mostly S, also O, C?, H?)	Fe, Ni, ~10% light elements (O, Si, S?)
	Physical state	Liquid outer, solid inner (?), possible molten silicate layer at core-mantle boundary	Liquid outer, solid inner

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