Seismic Evidence for a Liquid Martian Core

Abstract

This report presents a comprehensive analysis of seismic evidence supporting the conclusion that Mars has a liquid core. Using seismic data from the InSight mission, we examine the absence of S-waves, the reduction in P-wave velocity, and the application of Snell's Law at the core-mantle boundary. The findings indicate that Mars' core, with a radius of approximately 1830 km, is in a liquid state, fundamentally impacting our understanding of the planet's thermal history and geophysical evolution.

1 Introduction

The internal structure of Mars has been a subject of scientific investigation for decades. Understanding whether the Martian core is solid or liquid is critical for planetary formation models and for comparative planetology. Recent seismic data from NASA's InSight mission provide significant evidence for the liquid state of Mars' core, primarily through the behavior of seismic waves as they traverse different planetary layers.

The core of a planet plays a crucial role in its thermal and magnetic evolution. A solid or partially molten core would suggest that Mars may still have some geodynamo activity, whereas a completely liquid core aligns with the observation that Mars lacks a global magnetic field today. The analysis of seismic waves allows scientists to infer these internal properties with high confidence.

2 Seismic Observations and Core Radius

Seismic measurements offer direct insights into the internal composition of planets. InSight's seismic observations have determined the core radius of Mars to be approximately 1830 ± 40 km [1]. This value deviates significantly from estimates derived from simplified formulas, highlighting the necessity of incorporating seismic wave behavior and planetary density profiles in determining core properties.

The determination of the core size relies on the travel time of seismic waves and their interactions at the core-mantle boundary. By analyzing how these waves reflect and refract within Mars, researchers can infer the depth and extent of the core, which has been confirmed to be significantly different from earlier, more rudimentary calculations.

3 Absence of S-Waves: Evidence of a Liquid Core

S-waves, or shear waves, do not propagate through fluids due to the absence of shear strength in liquid states. The observation of a global S-wave shadow zone on Mars indicates that its core is not solid [2]. This method has been historically employed to confirm Earth's liquid outer core.

The physical explanation for this phenomenon lies in the fundamental nature of shear waves, which require a medium that can support shear stress. In a liquid, any applied shear force results in free displacement rather than elastic deformation, preventing the transmission of S-waves. The shadow zone observed on Mars thus provides compelling evidence for a liquid core.

4 Reduction in P-Wave Velocity

Unlike S-waves, P-waves, or primary waves, travel through both solid and liquid media but exhibit a reduction in velocity when transitioning from a rigid mantle to a less rigid core. Seismic data confirm a marked decrease in P-wave velocity at the Martian core-mantle boundary, supporting the conclusion that the core is in a liquid state [3].

P-wave velocities are influenced by the density and elastic properties of the medium. In a solid mantle, the material is more resistant to compression, allowing P-waves to travel at higher speeds. However, upon entering the liquid core, the reduced rigidity and increased compressibility cause a noticeable drop in velocity. This change is observed in the seismic recordings and serves as another key indicator of the core's liquid nature.

5 Snell's Law and Wave Refraction at the Core-Mantle Boundary

Snell's Law describes the refraction of seismic waves as they pass between materials of differing densities and elastic properties. At the core-mantle boundary, P-waves refract due to velocity differences, further substantiating the presence of a liquid core [3].

Mathematically, Snell's Law states that:

$$\frac{\sin i}{v_1} = \frac{\sin r}{v_2}, \tag{1}$$

where i is the angle of incidence, r is the angle of refraction, and v_1, v_2 are the P-wave velocities in the mantle and core, respectively. The reduction in velocity results in a smaller angle of refraction, affecting the overall wave paths observed in the seismic data.

The practical implication of this phenomenon is that seismic stations can detect specific travel time delays and angular deviations in P-wave arrivals, which match theoretical predictions for a liquid core. The observations from the InSight mission align precisely with this expected behavior.

6 Conclusion

The evidence presented in this report strongly supports the conclusion that Mars has a liquid core. The absence of S-waves, the reduction in P-wave velocity, and Snell's Law all align with the hypothesis of a liquid iron-nickel core with a radius of approximately 1830 km. These findings have profound implications for our understanding of Mars' internal dynamics and its evolutionary history.

A liquid core suggests that Mars once had the conditions necessary for a dynamo-driven global magnetic field, which may have dissipated over time due to cooling and core evolution. Understanding these internal processes provides critical insights into the past habitability of Mars and informs comparative studies with Earth and other terrestrial planets.

References

[1] P. Lognonné et al., "Mars Seismology," Annual Review of Earth and Planetary Sciences, 2023.

[2] Module 2: Seismic Shadow Zones and the Absence of S-Waves.

[3] Module 3: Snell's Law at the Core-Mantle Boundary and P-Wave Velocity Reduction.