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# First observations of core-transiting seismic phases on Mars

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**We present the first observations of seismic waves propagating through the core of Mars. These observations, made using seismic data collected by the InSight geophysical mission to Mars, have allowed us to construct the first seismically-constrained models for the elastic properties of Mars' core. We observe core-transiting seismic phase SKS from two farside seismic events detected on Mars and measure the travel times of SKS relative to mantle traversing body waves (PP, SS). SKS travels through the core as a compressional wave, providing information about its bulk modulus and density. We perform probabilistic inversions using the core-sensitive relative travel times together with gross geophysical data and travel times from other, more proximal, seismic events to seek the equation of state parameters that best describe the liquid iron-alloy core. Our inversions provide constraints on the velocities in Mars' core and are used to develop the first seismically-based estimates of its composition. We show that models informed by our SKS data favor a somewhat smaller (median core radius = 1780–1810 km) and denser (core density = 6.2–6.3 g/cm<sup>3</sup>) core compared to previous estimates, with a P-wave velocity of 4.9–5.0 km/s at the core-mantle boundary, with the composition and structure of the mantle as a dominant source of uncertainty. We infer from our models that Mars' core contains a median of 20–22 wt% light alloying elements when we consider sulfur, oxygen, carbon and hydrogen. These data can be used to inform models of planetary accretion, composition, and evolution.**

Mars | Core evolution | Planetary structure

## 1 Introduction

Recent results from the InSight geophysical mission to Mars (1) have revealed the layered nature of the red planet, illuminating its crustal structure (2–5), mantle velocities (6–9), and a mid-mantle seismic discontinuity associated with the phase transition of olivine (10). InSight has also recorded reflections from a large impedance contrast that is interpreted as the core-mantle boundary (CMB) (11). The Martian core is mostly, if not totally, liquid – the planet's tidal response can be used to rule out an entirely solid core (12–19). Formed early in Mars' history (20, 21), the core is an iron alloy rich in light elements with sulfur proposed as the main light element present based on Martian meteorite geochemistry (e.g. 22, 23). In contrast to the Earth and Mercury, no global magnetic field is currently generated by the Martian core, though crustal magnetism (24, 25) suggests the presence of a magnetic field early in the planet's history, pointing towards a possible evolution of Mars' core over the planet's lifetime (e.g. 26–28). Beyond these core facts, a great deal about Mars' central interior remains unknown, including the elastic properties and composition of its core (29).

Initial seismic observations using core-reflected seismic

waves (ScS) reported a core radius of  $1,830 \pm 40$  km (11), at the upper bound of pre-landing estimates (e.g. 13–16, 18, 30–34). These results are compatible with the independent findings of InSight's Rotation and Interior Structure Experiment (RISE) (35), which has measured the effect of the liquid core on the nutation of Mars (36). The inferred core radius and simultane-

### Significance Statement

Mars has a liquid iron alloy core at its centre. Using seismic data gathered by the InSight mission, we have made the first observations of seismic waves travelling through Mars' core. We use the travel times of core-transiting seismic waves, relative to ones which remain in the mantle, to constrain properties of the core and construct the first models of the elastic properties of the entire planet. Our results are consistent with a core rich in sulfur and oxygen, with smaller fractions of carbon and hydrogen.

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ous estimation of a relatively low core density has motivated questions about its composition: if only sulfur is considered as an alloying element, an implausibly high core sulfur fraction is required to match the core density whilst satisfying constraints on mass, moment of inertia, and tidal response of the planet (11). Though the observation of seismic waves reflected from Mars' CMB has helped constrain the core radius, and geophysical and cosmochemical inversions have sought to infer its average density and composition (e.g. 37), observations of seismic waves that directly probe core properties have been lacking to date.

Seismological investigations of core-transiting waves have been made on Earth for more than a century (38, 39), where both seismometers and hypocenters of large earthquakes are distributed around the globe. Analyses of their travel times have constrained the seismic properties of the liquid outer-core (e.g. 40, 41), supporting the presence of light elements (42), and enabling the estimation of its equation of state (e.g. 43). With just a single broadband seismometer and seismic sources smaller than those routinely detected on the Earth, comparable observations have proved more challenging on Mars. Here, we present and analyze the implications of new observations, which constitute the first detection of seismic waves transiting the Martian core.

## Observations and Analysis

**The events.** The InSight mission deployed a very broadband seismometer (44) onto the surface of Mars in late 2018, leading to the identification of numerous seismic events (45–48). To date, only two seismic events have been identified as located on the opposite hemisphere of Mars to the InSight lander (49). These events (Fig. 1 A) are designated S0976a and S1000a, corresponding to the first seismic events detected on Sols (InSight Martian mission days) 976 and 1000, respectively.

These events were located using phases identified as PP and SS – waves which travel down to a depth of nearly 1200 km in the Martian mantle, and reflect from the surface of Mars mid-way along their path. The Mars Quake Service (MQS) estimated the epicentral distances of S0976a and S1000a to be  $146^\circ \pm 7^\circ$  and  $128^\circ \pm 19^\circ$ , respectively, with Mars-calibrated magnitudes (50)  $M_w^{Ma}$  of 4.2 and 4.1, respectively (47, 49). Uncertainty on marsquake locations is considerable, because they depend on seismic models of Mars' layered crust and mantle and, for source depth determination, the unequivocal identification of depth phases (e.g. 7, 8). Fortunately, orbital imaging combined with data from InSight revealed S1000a to be an impact at a distance of  $125.9^\circ$  and a backazimuth of  $\sim 34^\circ$  (51), though the exact time of the impact is not known. We are therefore able to precisely locate the source of S1000a, and fix its depth to zero, removing this source of uncertainty from our work.

**Phase detection.** At the distances corresponding to S0976a and S1000a, SKS, which travels as a shear wave in the crust and mantle and as a compressional wave in the core (Fig. 1 A), will be the first core-transiting phase to arrive (Supp. Fig. S11). Core phase PKP, which travels its entire path as a compressional wave, is not predicted at these distances, as the expected velocities of the core and mantle require PKP arrivals to be confined to areas close to the antipode of a marsquake, unlike the wider detection zone on Earth.

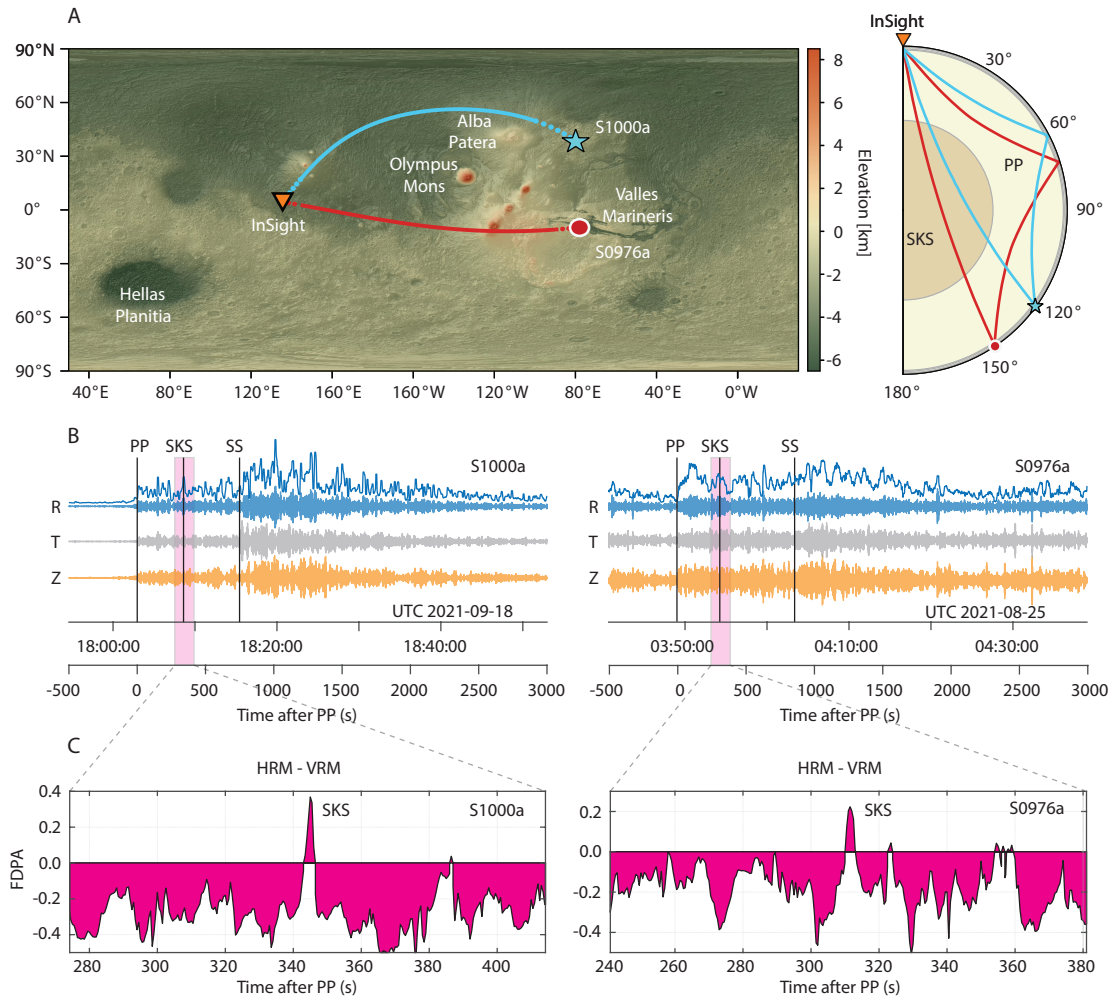
SKS arrives between the PP and SS signals (Figs. 1B) and with an amplitude comparable to that of PP on the radial component seismograms (Supp. Figs. S15, S16). 'Radial' is defined as the horizontal direction along the great circle path from the event to the station, and is perpendicular to the 'transverse' (horizontal) component and the vertical component. At the distances corresponding to S0976a and S1000a, SKS has key distinctive attributes that we exploit to facilitate its detection: SKS should be a vertically-polarized shear wave (SV) with little horizontal shear (SH) motion on the transverse component (assuming seismic anisotropy is weak); due to its steep incidence angle, SV energy of SKS should be linearly polarized and strongest on the radial component of motion; SKS is expected to have a waveform related to the shape of SS (assuming minimal complexity introduced at the SS bounce point) through a Hilbert transform; SKS arrives in a time-window where few interfering phases should be present (travel time curves are shown in Supp. Fig. S11) so that arrivals detected with the correct characteristics can be assigned to be SKS with reasonable confidence. Radial anisotropy, which has been detected in the Martian crust (52–54), should not impact these attributes of SKS unless there is an as-yet undiscovered more complex anisotropic texture present.

Detection of SKS, and measurement of its travel time relative to either PP or SS, is made using several different methods. These can be broken into two categories: (i) arrival detection techniques, which seek to detect wavepackets of energy in the seismic record with the correct characteristics, and (ii) correlation-based methods, which find the time delay between different packets of energy associated with seismic arrivals. Three arrival-based methods (Methods A – C) and two correlation-based methods (Methods D – E) were applied to the data.

We present here results from frequency-dependent polarization analysis (FDPA), an arrival detection technique which assesses whether signals are present at a range of frequencies and have the required polarization. This method (labeled as Method A in this work) has previously been implemented for InSight data and successfully identified the core-reflected ScS phases (11) as well as the minor-arc surface waves on Mars (5). Fig. 1 depicts the seismic data together with the excess of total horizontally-polarized energy as compared to vertically-polarized energy as a function of time since the MQS PP arrival time. Glitches (i.e., non-seismic spikes in the recorded data) can complicate the interpretation of seismic phases on InSight data (55, 56), and have been removed (see also supplementary section S2.8).

For event S1000a, the SKS signal is identified using the FDPA method (Fig. 1 C) as the horizontally-polarized energy arriving  $\sim 340$  s after PP (Method A in Table 1). This is the most coherent signal in the relevant time window.

In addition to Method A, measurements of SKS differential travel times were also sought for S1000a using the four other complementary methods, B – E (see Table 1 and supplemental material section S2), with the two alternate arrival detection methods (B & C) able to detect SKS. The three different arrival detection methods (A – C) enhance slightly different characteristics of the waveform, with different optimal frequency bands, and therefore find slightly different differential arrival times. The two cross-correlation methods (D & E) were unable to measure SKS differential travel times for S1000a,



**Fig. 1.** Location map, seismic data and frequency-dependent polarization analysis for events S0976a and S1000a. (A) Locations of the two farside events, S0976a (red circle) and S1000a (blue star), and the InSight seismometer (orange triangle). The dotted lines show the SKS path in the mantle, the solid lines depict the part of the SKS path in Mars' core (surface topography model from 57). Raypaths of seismic phases SKS and PP are shown in the same colors as events. SKS travels through the core; PP remains in the mantle. PP may have multiple arrivals at this epicentral distance (10); we show the path of the first propagating wave. SS, used together with PP as a reference phase, has a very similar path to PP (Figs. S15-16). (B) Radial (blue), transverse (gray), and vertical (orange) component seismograms for S1000a (left) and S0976a (right), together with travel time picks. Above the radial component we show its envelope. (C) Horizontal-vertical summed FDPA intensity as a function of time (analysis Method A). The strong horizontally polarized signal is interpreted as the arrival of SKS.

possibly due to the more emergent nature of the SS signal for this event (49). We note that the PP and SS arrivals determined using Method C were employed to get the SKS differential travel times reported for Method A. Section S2.1 of the supplement summarises and compares the five different methods employed.

The SKS signal from S0976a is identified using the FDPA method (Method A in Table 1) as the horizontally polarized energy arriving  $\sim 310$  s after PP (Fig. 1 C). In this case, the two cross-correlation based methods (D & E) also found signals identified as SKS, and one further waveform identification method (B) found an SKS arrival. The final waveform identification technique (Method C) did not find a single observation clearly identifiable as SKS, we include their estimate here for completeness. The SKS-PP measurements have a range of 14 s whilst the SS-SKS times have a range of 9 s. The use of the cross-correlation methods provides further justification of our

identification of SKS. Methods D and E use the SS waveform as a template to correlate with SKS, so that we know the two wavepackets have related shapes, as we would expect for waves generated by the same marsquake.

Environmental noise, particularly that due to wind, can be prominent on InSight's seismic records (46, 48, 58–60). We verify, using the method of (60), that the signals identified as SKS for both events are not associated with excess environmental energy (see supplementary section S2.7). In light of this analysis and the expected amplitudes of SKS (supplementary section S3.4) we conclude that our SKS detections and associated travel times are robust. In this investigation, it has proven vital to have 3-component recordings to ensure the phase identified was indeed SKS; future missions to other planetary bodies (e.g., 61) will benefit if 3-component seismometers can be employed in preference to vertical-component instruments alone.

Method	S0976a			S1000a		
	SS-PP (s)	SKS-PP (s)	SS-SKS (s)	SS-PP (s)	SKS-PP (s)	SS-SKS (s)
A (arrival det.)	858.5	311.0	547.5	–	344.2	401.4
B (arrival det.)	853.4	298.3	555.1	752.3	334.8	417.5
C (arrival det.)	859.0	310.0*	549.0*	745.6	339.0	406.6
D (cross-corr.)	855.0	309.0	546.0	–	–	–
E (cross-corr.)	846.0	297.4	548.6	–	–	–
Average	854.4	303.9	549.2	749.0	339.3	408.5
St. dev.	5.2	7.1	4.1	4.7	4.7	8.2

**Table 1. SKS differential travel times measured using five different methods, three arrival detection methods and two cross-correlation methods (see supplementary materials for details). Times marked \* are insufficiently confident for use in inversions.**

The average differential travel times of all reliable observations are used in our inversion, with an assigned uncertainty of 10 s. This assigned uncertainty is greater than the standard deviation of the travel time picks, in order to account for other sources of uncertainty. For example, potential three-dimensional (3D) velocity variations in the mantle can also affect differential travel times (18). We quantify these using ray theoretical calculations through candidate thermochemical models of Mars’ interior (as in 62) and find that they are comparable to the assigned observational uncertainty.

We can assess, using forward modeling (63), how uncertainties in the event depth and epicentral distance would affect SKS differential travel times. The source depth for S0976a is not well constrained, as no clear depth phases (or surface waves) are identified. A standard MQS event depth of 50 km is assigned to this event; changing the source depth by 30 km changes the differential travel times by less than 5 s (Fig. S12) as the arrival times of both SKS and the mantle reference phase are affected in the same way by changing the event depth. Effects are more substantial when the epicentral distance is altered – changing the epicentral distance by 5° modifies PP-SKS time by around 10 s, but around 30 s for SS-SKS differential travel times. Thus, the uncertainty in the locations of S0976a makes it challenging to accurately assess the seismic velocity inside Mars’ core. The known impact location obviates this concern for S1000a.

Shear wave phase SKKS, which is reflected from the underside of the CMB, and Sdiff, which diffracts along the CMB (Supp. Figs. S15 and S16), are not observed for either event; using current models (11) we anticipate they would both arrive approximately 100 s after SKS, with radial and transverse polarizations, respectively. The similar travel times of these two phases are due to the very small velocity difference expected between compressional wavespeed in Mars’ uppermost core and shear wavespeed in Mars’ lowermost mantle, so that traveling across the uppermost core or along the CMB take similar amounts of time. The absence of identifiable arrivals permits some possible inferences to be made about the lowermost mantle. SKKS travels to and from the CMB with a more oblique angle than SKS; if the lowermost mantle contains any partial melt (e.g. 64) SKKS would be more attenuated than SKS. The absence of Sdiff may be caused by a similar phenomenon. Alternatively, Sdiff is observed at relatively long periods on Earth (e.g. 65), which would make it difficult to detect given the range of frequencies typically usable on Mars. While Pdiff has been detected (9, 49, 51), it remains the case that Sdiff has not yet been observed in marsquake waveforms.

## Core properties

We first compare our observations to predictions from the InSight\_KKS21\_GP model (3, 6, 11). This model was created with Bayesian inversions using a geophysical parameterization (6, 11) and has been adapted to have a three-layer, 48 km thick crust, consistent with (3, 6, 7, 56). We note (i) that the P-wave velocities in this model are not constrained by seismic data below a depth of 800 km (6), which means that predictions of PP arrival times might be less reliable than SS; and (ii) the core velocity structure in this model is not seismically constrained. The observations for S0976a are close to predictions for the MQS epicentral distance (within 10 s for both PP-SKS and SKS-SS for an event depth of 50 km). The same model predicts times for S1000a, known to be an impact at a distance of 125.9°, which are within 20 s for SKS-PP and 15 s for SS-SKS. The PP-SS time of S1000a is within two seconds of the prediction made using InSight\_KKS21\_GP, suggesting that the discrepancy between our observed and predicted SKS times may be in part due to the lack of previous seismic constraints on the elastic properties of Mars’ core.

While a core sulfur content close to the eutectic makes the formation of an inner core in Mars unlikely at temperatures above ~ 1200-1500 K (29, 66), the detection of SKS signals from S0976a and S1000a places a bound on the maximum size of any Martian inner core. As SKS reaches a minimum radius of ~ 750 km, we expect that an inner core, if one exists, would be smaller than this radius. Further constraints on the presence or absence of an inner core are expected from InSight’s RISE instrument (35).

With two events and two reference phases, there are four differential travel times that must be satisfied by a reasonable seismic model of Mars’ interior. Relying on the crust and mantle of InSight\_KKS21\_GP and systematically changing the velocity at the CMB and core velocity gradient, we can seek the properties of the core that best fit the data. Such an analysis (Fig. S14) suggests that a range of core properties are compatible with the observations. However, the core velocity and gradient of InSight\_KKS21\_GP do not make predictions which fall close (within one standard deviation) to the average SKS differential travel times. Instead, this forward modeling suggests that the seismic velocity of the core may be higher than in that model, while the velocity gradient might be slightly lower. It would be possible to take an existing model of mantle properties and simply seek the core properties which best fit the SKS differential times. However, such an analysis would not allow for the possibility that InSight\_KKS21\_GP does not represent the velocities of the crust and mantle accurately. Moreover, it would not

278 take into account the uncertainty in the depth and epicentral  
279 distance of S0976a. Finally, such an approach would preclude  
280 a joint analysis of the correlated uncertainties in mantle and  
281 core structure across different mantle-inversion strategies. A  
282 joined-up approach to the modeling of Mars’ interior allows  
283 us to avoid inadvertently compensating for imperfect models  
284 of the mantle by selecting incorrect properties for the core –  
285 trade-offs can be more easily visualised and understood. Thus,  
286 we opt to invert our data for new models of Mars’ interior.

287 **Seismic inversion.** Exploiting core-transiting phases, we can  
288 refine estimates of the internal properties of Mars. Indeed,  
289 without core-transiting phases, the elastic properties of the  
290 core can only be constrained indirectly and generally under  
291 the assumption that the core is composed of an iron-sulfur  
292 alloy (e.g. 14–16, 30). In (7, 8, 11), the core radius was  
293 estimated using the travel times of core-reflected waves to-  
294 gether with geophysical data. Here we invert seismic data  
295 including the relative travel times of core-transiting phases,  
296 requiring that the resulting models fit the mean planetary  
297 density ( $3.935 \pm 0.0012 \text{ g/cm}^3$ ) and mean normalized moment  
298 of inertia of Mars ( $0.3634 \pm 0.00006$ ) (13).

299 We conduct three separate sets of Bayesian inversions, two  
300 of which use the SKS differential travel times presented here.  
301 The first set of inversions – hereafter referred to as producing  
302 “*geophysical*” models – use the travel times from direct, re-  
303 flected, and converted crustal, mantle, and core seismic phases  
304 gathered in (7), and have a similar modeling approach for the  
305 mantle parameterization. The second and third sets of inver-  
306 sions use the “*geodynamical*” parameterization of (67) with  
307 their dataset of direct and reflected mantle- and core-sensitive  
308 travel times (8). The third set of inversions differs from the  
309 second in that it does not include SKS differential travel times,  
310 so that it can serve as a point of reference. Full details of  
311 inversion methods are provided in supplementary section S4.

312 All sets of inversions are parameterized assuming that the  
313 core’s thermo-elastic properties can be described by an isen-  
314 tropic third-order Birch-Murnaghan equation of state (68).  
315 The core’s elastic properties are therefore described by three  
316 parameters: density,  $\rho_{CMB}$ , the adiabatic bulk modulus,  
317  $K'_{CMB,S}$ , and its pressure derivative,  $K''_{CMB,S}$ , referenced to  
318 CMB conditions. As Mars has no currently active geodynamo,  
319 its core may be presently fully conductive, or it may be that  
320 the convective region in the core generates insufficient excess  
321 entropy to produce a magnetic field (17, 27, 28, 69); there-  
322 fore, a temperature profile along an isentrope is a first-order  
323 assumption, commonly employed in modeling planetary cores.  
324 A hotter, isothermal core would change the predicted CMB  
325 velocity by only  $\sim 0.5\%$ .

326 The elastic models produced are sieved using the require-  
327 ment that they fit the SKS differential travel times within  
328 twice the uncertainty bounds. This is a conservative choice,  
329 intended to account for potential differential travel time vari-  
330 ations due to 3D velocity variations within the mantle. It  
331 effectively increases the importance of fitting the SKS differ-  
332 ential travel times over the mantle phases, which are already  
333 the subject of significant investigation (7–9). Inversions were  
334 conducted using both the *geophysical* and *geodynamical* pa-  
335 rameterizations for the geochemically-derived model mantle  
336 composition EH45 (23). Compositions described by LF (22),  
337 TAY (70), and YMD (71) were also used (see supplementary  
338 section S4). Seismic models are shown in Fig. 2 A and B; mod-

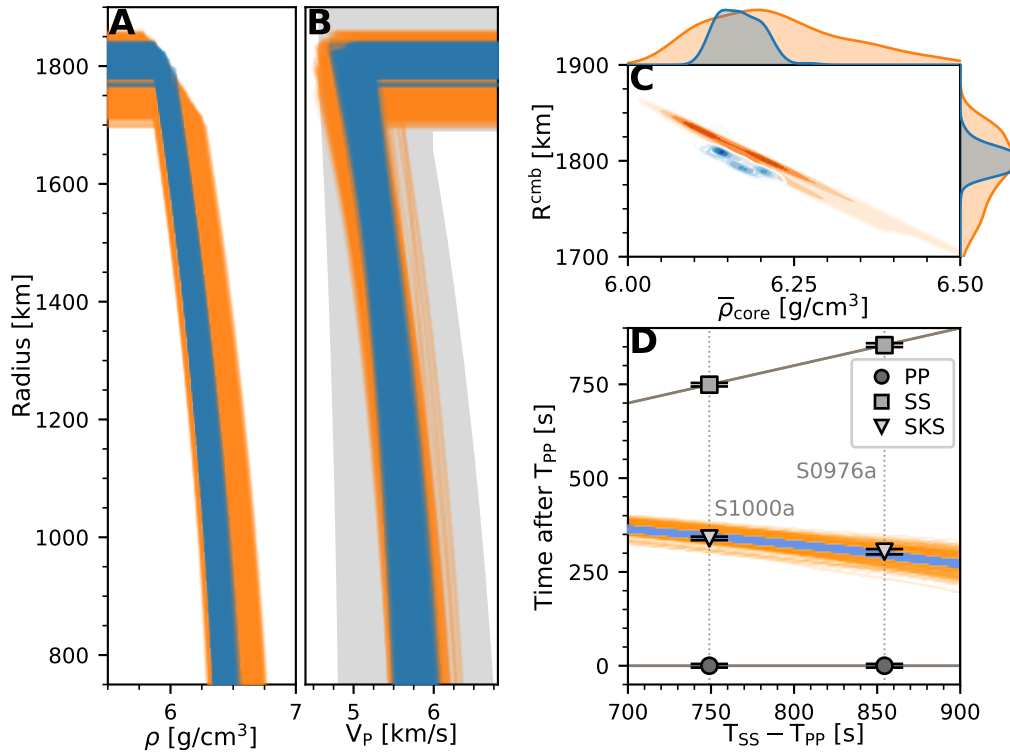
els including their crust and mantle components are shown in  
supplementary Fig. S21.

Information on the travel times of core-transiting phases  
has allowed us to constrain the elastic properties of the core  
much more directly than before (compare gray and colors  
in Fig. 2B) and, importantly, without making assumptions  
about the composition of the core and properties of its metallic  
alloy. Our inversion results show an expected anti-correlation  
between core radius and density – in order to fit the mass and  
moment of inertia constraints applied, models with a larger  
core must have a lower core density. Assuming an EH45 model  
to inform the mantle composition, we find core radii of 1814 km  
(interquartile range, IQR: 1804 – 1823 km) and 1799 km  
(IQR: 1773 – 1819 km) for the *geophysical* and *geodynamical*  
inversions. Assumptions about mantle composition affect  
these estimates somewhat: the LF and TAY compositions  
result in a 6 km and 15 km smaller core, while the YMD  
composition implies the smallest core, with a median radius of  
1779 km. Therefore, while modeling choices lead to different  
distributions of the core radii (see the histogram on the right  
of Fig. 2C), the medians of all distributions fall within  $\pm 17$  km  
of each other.

These values can be compared to the first estimates based  
on ScS travel times (waves reflected from Mars’ CMB) of  
 $1830 \pm 40$  km (11),  $1840 \pm 10$  km (37),  $1845 \pm 25$  km (7),  
and  $1773 \pm 41$  km when crustal constraints are used in the  
*geodynamical* inversion of (8). Thus, while mostly consistent  
within the uncertainties quoted, our results support a slightly  
smaller core.

When we compare models constructed using EH45 to in-  
form mantle composition, median bulk core densities,  $\rho_c$ , are  
 $6.21 \text{ g/cm}^3$  (IQR:  $6.18 - 6.24 \text{ g/cm}^3$ ) and  $6.25 \text{ g/cm}^3$  (IQR:  
 $6.18 - 6.34 \text{ g/cm}^3$ ) for the *geophysical* and *geodynamical* mod-  
els, respectively. These average core densities depend on  
assumed mantle composition; for example, in the *geophysical*  
inversions, replacing the EH45 composition model with the  
TAY one reduces  $\rho_c$  by  $0.05 \text{ g/cm}^3$ , while instead using LF in-  
creases  $\rho_c$  by  $0.01 \text{ g/cm}^3$ . The largest median bulk core density  
are obtained in the *geodynamical* inversions using the YMD  
mantle composition ( $\rho_c = 6.35 \text{ g/cm}^3$ , IQR:  $6.27 - 6.50 \text{ g/cm}^3$ ).  
Accounting for uncertainties due to assumptions of mantle  
composition, the range of median core densities we obtain in  
this study,  $\rho_c = 6.16 - 6.35 \text{ g/cm}^3$ , is higher than the earlier esti-  
mates of  $6.0 \pm 0.3 \text{ g/cm}^3$  (11). Within uncertainty, they overlap  
with estimates obtained by (37) and (7) of  $6.15 \pm 0.046 \text{ g/cm}^3$   
and  $6.1 \pm 0.1 \text{ g/cm}^3$ , respectively, and allow us to rule out some  
of the lighter core scenarios reported in (11).

The P-wave velocity at the top of the core,  $V_{CMB}$ , is  
seismically-constrained for the first time by our observation  
of SKS. We find that, at the CMB, the median seismic P-  
wave velocity ranges from  $\sim 4.89 - 5.05$  km/s, depending on  
assumptions of mantle composition. Using EH45 to inform  
the mantle composition, the *geophysical* and *geodynamical*  
models presented here have median CMB core velocities of  
 $4.94$  (IQR:  $4.87 - 5.05$  km/s) and  $4.89$  (IQR:  $4.78 - 5.01$  km/s)  
respectively. These estimates are lower than those measured  
for pure liquid iron (e.g.  $5.14 \pm 0.14$  km/s at 20.5 GPa and  
2,300 K, 72), providing a further, independent argument in  
favor of a substantial fraction of light elements in the Martian  
core. *Geodynamical* inversions using the seismic travel time  
dataset of (8), but excluding the core-transiting signals, re-



**Fig. 2.** Inversion results for the seismic properties of Mars' core. *geophysical* inversion results are shown in blue, *geodynamical* results are shown in orange. (A,B) Density and seismic velocity models for Mars' core. In panel (B), the gray area indicates the results of *geodynamical* inversions carried out without using the SKS differential travel times. (C) Average density and core radius of Mars. The histograms above and to the right display the posterior distributions of the average density and core radius respectively. (D) Observed (black) and predicted (colours) travel times.

400 sult in a faster median  $V_{CMB}$  of 5.10 km/s and much greater  
 401 uncertainties ( $\sim 110\%$  broader IQR: 4.87 – 5.35 km/s). The  
 402 extra information contained in the SKS travel times allows  
 403 us to substantially narrow the estimates of  $V_{CMB}$  relative to  
 404 pre-mission predictions (15, 16, 18, 30, 32) (Fig. 2). With  
 405 two events providing SKS observations, there is necessarily  
 406 some degree of trade-off between the seismic velocity at the  
 407 CMB and the velocity gradient in the core. Nonetheless, the  
 408 velocities of our model families are tighter both at the CMB  
 409 and at depth when we include the SKS data.

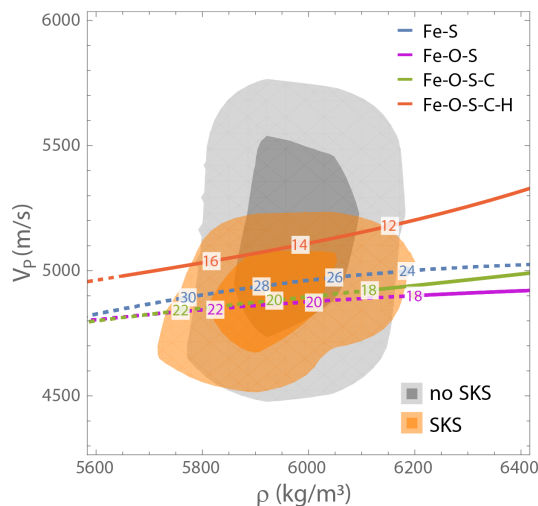
410 The core radius, velocity, and density distributions provided  
 411 by the *geophysical* and *geodynamical* inversions have different  
 412 IQRs (Fig. 2). In addition to the distinct inversion priors  
 413 of the two methods, there are several factors that contribute  
 414 to these differences: first the *geodynamical* parameterization  
 415 (17) relies on a larger number of free parameters than the  
 416 *geophysical* parameterization (6). Second, the sensitivity of  
 417 the inverted parameters to the seismic data is different for  
 418 each method (67, 73). Finally, different choices were made in  
 419 assembling the travel time datasets used in the two inversion  
 420 schemes (7, 8).

421 While our inversions are designed to self-consistently predict  
 422 velocities at all radii below the CMB – thereby providing  
 423 estimates of velocity throughout the core – the absence of  
 424 deeply-diving paths reduces our ability to constrain velocity  
 425 gradients. Thus, because the paths traversed by our SKS  
 426 observations do not reach the center of Mars (Fig. 1), we  
 427 display the models only in the top 1000 km of the core.

428 By constructing a one-dimensional model of the planet's  
 429 elastic properties, we implicitly assume that the portions of  
 430 crust and mantle of Mars transited by waves from S0976a and  
 431 S1000a are not too dissimilar to that under InSight. Surface  
 432 wave analysis indicates that, while crustal velocities are similar  
 433 north and south of the dichotomy, crustal thicknesses vary  
 434 substantially (5, 53); this is one of the reasons that we have  
 435 assigned uncertainties larger than the measurement standard  
 436 deviations to our differential travel time observations. We  
 437 have also assumed that there is no distinct molten layer atop  
 438 Mars' core-mantle boundary (64). The possible existence of  
 439 a compositionally-distinct molten layer would not only affect  
 440 estimates of core radius and velocities in the lowermost mantle,  
 441 but also those of temperature and composition at the CMB.  
 442 As such, joint investigations of the core and lowermost mantle  
 443 of Mars will be an important future step.

**Interpretations.** Many previous works modeled the core under  
 444 the approximation of an iron-sulfur alloy, though it is reason-  
 445 able to assume that Mars' core contains notable fractions of  
 446 other light elements (e.g. 11, 30, 37, 74). Inverting for the  
 447 parameters governing the core equation of state allows to con-  
 448 sistently compute the density and velocity of the core without  
 449 making recourse to any specific core composition. The result-  
 450 ing core density and velocity can then be compared to that  
 451 corresponding to liquid iron alloys at Mars' core pressure and  
 452 temperature conditions to constrain the nature and abundance  
 453 of light elements.  
 454

455 We use the seismically-derived models presented here to



**Fig. 3.** Core velocity and density at the CMB compared with equation of state predictions. Results from the *geodynamical* inversions with and without SKS data are shown, with the lightly and strongly shaded areas indicating 90% and 50% of the models, respectively. The lines correspond to predictions for liquid Fe-S, Fe-O-S, Fe-O-S-C and Fe-O-S-C-H alloys. Moving along each line corresponds to variations in the amount of sulfur present (wt% S is indicated by the numbers along the line). Lines are dashed where the alloys contain more than 18 wt% sulfur. When present, carbon is at saturation level and hydrogen is fixed at 1 wt%.

While Fe-S and Fe-O-S alloys could provide a match to the SKS-informed core models, they do so at unreasonably high sulfur fractions (e.g. estimates of reasonable S fractions from 30, 74, are 17-19%). Inclusion of C, even at the solubility limit, only marginally reduces the sulfur fraction required. However, adding hydrogen to an Fe-S-O-C alloy increases the core velocity substantially, while requiring much less sulfur to account for the density. The effect of varying CMB temperature and pressure is to broaden these lines, increasing both the range of possible velocities for a given density by  $\sim 100$  m/s (Fig. S23) and the width of implied posterior elemental abundance distributions. Finally, we note that an Fe-Si alloy would produce seismically impermissible velocities  $> 6000$  m/s (77), independently reinforcing the conclusion, drawn from assessments of the oxidizing conditions of Mars' formation, that only a negligible amount of Si is present in Mars' core (e.g. 30).

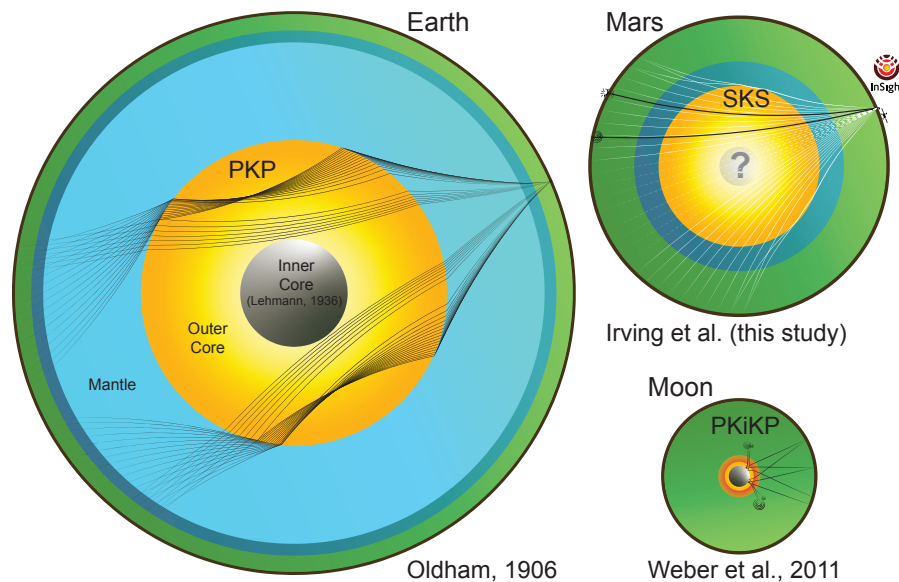
We now turn to the results of our compositional inversions; full details of the methods used are provided in supplementary sections S4.4-S4.5. We find that the assumptions made when seeking to match the density and velocity of our core models with compositional models are as important as the seismic inversion choices, and in some cases can restrict the space of allowed core velocity-density space even more tightly than the SKS observations. When we use EH45 to model the Martian mantle and assume that O, S, C, and H are the light elements in the core, we infer core compositions that contain a median of 16.5 wt% S for the *geodynamical* models and 15.4 wt% S for the *geophysical* models, with IQRs of 15.1 – 18.4 wt% and 14.6 – 16.3 wt% respectively. The corresponding median core fractions of other light elements are 2.9 – 3.2 wt% O (IQRs span 2.7 – 3.7 wt% for the two families of models), medians of 1.2 – 1.4 wt% C (IQRs span 1.0 – 1.5 wt%) and 0.5–0.6 wt% H (IQRs span 0.2 – 0.7 wt%). The S and H content of the core are, as expected, anti-correlated (Fig. S24) – a core with appropriate density can be achieved with either very little H and a larger amount of S, or a larger fraction of H and a lower amount of S. The choice to model the core as saturated in C has an impact of  $\sim 1$  wt% on the quantities of all the other light elements interpreted to be present in the core. The choice of the equation of state for liquid FeH is also critical for these compositional inferences. Thus we do not stress precise compositional inferences but rather argue that the core-traversing waves presented here are indicative of a core with a high fraction of light elements.

Estimates of the total light element abundance of the Martian core are largely controlled by constraints on core mass, while constraints on core P-wave velocities help to discriminate between different light-element scenarios. Using EH45 to inform the mantle, our compositional inversions find that the Martian core contains a median of 20.3 – 21.4 wt% total light elements (IQRs span 19.5 – 23.4 wt%) for the *geophysical* and *geodynamical* models. This is higher by about  $\sim 1$  wt% than the total light element composition one would obtain without SKS travel time data. When considering alternative mantle compositions to EH45 (LF, TAY or YMD) and resulting mineralogies, median total light element abundances are only affected by  $< 1$  wt%, with the LF composition suggesting the smallest (median of 19.8 wt%) and the YMD composition implying the largest (median of 21.6 wt%) total light element abundances.

seek out physically-consistent core compositions for Mars. Specifically, we identify the combinations of light element abundances in a multi-component Fe-O-S-C-H alloy, which can produce the P-wave velocity  $V_{CMB}$  and  $\rho_{CMB}$  of the core alloy. Although our seismic inversions also contain information about  $K'_S$ , this parameter is less well-constrained due to the aforementioned weak constraint on velocity gradient with depth provided by the SKS travel times. Consequently, while a subset of compositional models can reproduce the velocity across the full range of core pressures, we do not limit our discussion to only those core compositions. As for the light element content, we invert for the fraction of S and H in the core, while fixing the amount of O to that of S and mantle FeO following (75), as O is incorporated in the metallic core alongside S during core differentiation. Carbon also is directly related to S, as it is assumed to be at the solubility limit in Fe-S (76).

We first compare the results of our inversions with equation of state predictions for the velocity and density of different alloys with a variable light element content (Fig. 3). We see that when core properties are not informed by SKS, many of the retrieved models have velocity-density combinations incompatible with core-candidate liquid Fe-alloys, with seismic velocities above those of alloys with  $> 1$ wt% hydrogen. The introduction of SKS travel time constraints narrows the permissible velocity-density range for the Martian core, in a way that restricts it to a region that can be accounted for by a number of liquid iron alloys of plausible light element content. Therefore, while not pointing at a specific core composition, the travel times of core-transiting seismic phases provide independent arguments in support of a volatile-rich core, as put forward on the basis of cosmochemical arguments which encompass the chemical and isotopic analysis of Martian meteorites (e.g. 22, 23, 34, 70, 71) and core differentiation models (e.g. 30, 74, 75).





**Fig. 4.** Schematic showing core-transiting ray-paths through the three seismically-explored planetary bodies: Earth (38), Mars and the Moon (78). Earth’s inner core was discovered some thirty years after the outer core (79). Colors within each body correspond to different dominant minerals and phases. Mars has an upper mantle dominated by olivine (shown in green), and a mantle discontinuity corresponding to the post-olivine phase transition (10) indicated by dark blue. On Earth, below the olivine-rich upper mantle and the transition zone, the lower mantle is predominantly bridgemanite (light blue); the lowermost mantle is not shown. The liquid metallic core of each body is shown in shades of yellow, while on the Moon and Earth the inner core is shown in gray, and the Moon’s partial melt layer is shown in red.

552 Seismology has long been used to make inferences about  
 553 the size and composition of Earth’s ~7,000 km diameter core,  
 554 and permitted the discovery of the much smaller lunar core  
 555 (Fig. 4). Estimates for the light elements present in the lunar  
 556 core vary, but suggest a negligible fraction of silicon and oxygen,  
 557 and relatively high fractions of sulfur and carbon (29, 80–82).  
 558 Uncertainties in understanding the lunar core’s composition  
 559 are substantial in part because core-transiting phases reported  
 560 by (78) were observed using challenging Apollo-era data. New  
 561 observations made by the Farside Seismic Suite (83) will shed  
 562 further light on the lunar core. On Earth, seismic velocities  
 563 and density have been used to better our understanding of the  
 564 light elements present in the core. Earth’s liquid outer core is  
 565 suggested to have only about half the fraction of light elements  
 566 advocated for Mars’s core, as it is likely to contain less than  
 567 2 wt% S, along with no more than 4 wt% Si, less than 6 wt%  
 568 O and up to 0.25 wt% H (e.g. 84). We stress however, that the  
 569 limit of 2 wt% S in the Earth’s core is driven by geochemical  
 570 arguments and volatility trends (e.g. 85, 86), while on the sole  
 571 basis of thermo-elastic properties, Earth’s outer core could  
 572 contain up to 10 wt%S (87, 88), or as much as 14.4 wt%S  
 573 if it is assumed to be the only light element present (84).  
 574 Consideration of the condensation chemistry of elements in  
 575 the solar nebula and feeding zones for planetary formation and  
 576 accretion leads to the expectation that planets formed further  
 577 from the Sun will contain a larger amount of volatile elements  
 578 (89, 90). A precise determination of the light element budget  
 579 of Mars’ core, based on combined geophysical observations,  
 580 mineral physics, petrological and cosmochemical constraints  
 581 will be vital in comparing the processes at play during the  
 582 formation of the Earth and Mars. Such a comparison could  
 583 reveal the extent to which differences between Earth and Mars  
 584 are a consequence of the material which accreted to form the  
 585 two planets and which are due to the physical conditions (e.g.,

586 pressure, temperature, and oxygen fugacity) present during  
 587 planetary differentiation (e.g. 29, 37).

## 588 Conclusions

589 We have detected core transiting phase SKS from two distant  
 590 events on Mars. The travel times of these phases, relative to  
 591 travel times of mantle-sensitive signals, are used to pro-  
 592 duce models of the seismic properties throughout Mars, and  
 593 represent the first interior models that are informed by core-  
 594 transiting seismic waves. Our observations provide the first  
 595 direct constraints on the elastic properties of the Martian  
 596 core. We find that the median seismic velocity at the top of  
 597 the Martian core is ~ 4.9 – 5.0 km/s, with the precise  
 598 value depending on the mantle-sensitive seismic data, assumed  
 599 mantle composition, and inversion methods employed. The  
 600 seismically-determined density and velocity, estimated without  
 601 any a priori assumption on composition, can be compared to  
 602 those of an Fe-O-S-C-H alloy at Mars’ core conditions to con-  
 603 strain the abundance of light elements. This comparison yields  
 604 further evidence in favor of a high fraction of light elements  
 605 alloyed with iron, independently of the inversion method, man-  
 606 tle chemistry, and mantle travel-time dataset used. Future  
 607 geophysical missions to Mars will be vital to refining models  
 608 of the Martian core beyond these first seismological estimates,  
 609 and a multi-location network of seismometers (61) may prove  
 610 critical to enhancing our knowledge of Mars’s deep interior.  
 611 Meanwhile, continued analysis of the InSight seismic data  
 612 will prove helpful in further refining models of Mars’ interior  
 613 structure.

## 614 Materials and Methods

615 We used seismic data from the InSight mission in this research.  
 616 InSight waveform data and the Mars Quake Service catalogue,

617 which contains details of all events and phase picks for events  
 618 up to the end of June 2022, are available from the IRIS-DMC,  
 619 NASA-PDS, SEIS-InSight data portal and IPGP data center  
 620 (47, 91, 92). SKS signals were picked using five different meth-  
 621 ods, labelled methods A-E in this paper. Full details of the  
 622 processing steps needed are described in the supplementary  
 623 material, in section S2. Two different inversion schemes were  
 624 used to obtain models of Martian density and seismic velocities.  
 625 Detailed descriptions of these schemes, which follow the meth-  
 626 ods of (7, 8), are provided in supplementary section S4. Details  
 627 of the compositional inversions are also given in supplementary  
 628 section S4.

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