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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

s information about its bulk modulus and density. We perform probabilistic inversions using the core-sensitive relative travel times together with

6 gross geophysical data and travel times from other, more proximal, seismic events to seek the equation of state parameters that best describe

7 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/cm³) core compared to previous estimates, with a P-wave velocity of 4.9–5.0 km/s at the core-mantle

10 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

¹² inform models of planetary accretion, composition, and evolution.

Mars | Core evolution | Planetary structure

Introduction

Recent results from the InSight geophysical mission to Mars (1)2 have revealed the layered nature of the red planet, illuminating 3 its crustal structure (2-5), mantle velocities (6-9), and a 4 mid-mantle seismic discontinuity associated with the phase 5 transition of olivine (10). InSight has also recorded reflections 6 from a large impedance contrast that is interpreted as the coremantle boundary (CMB) (11). The Martian core is mostly, if 8 not totally, liquid - the planet's tidal response can be used to 9 rule out an entirely solid core (12–19). Formed early in Mars' 10 history (20, 21), the core is an iron alloy rich in light elements 11 with sulfur proposed as the main light element present based 12 on Martian meteorite geochemistry (e.g. 22, 23). In contrast 13 to the Earth and Mercury, no global magnetic field is currently 14 generated by the Martian core, though crustal magnetism 15 (24, 25) suggests the presence of a magnetic field early in the 16 planet's history, pointing towards a possible evolution of Mars' 17 core over the planet's lifetime (e.g. 26-28). Beyond these 18 core facts, a great deal about Mars' central interior remains 19 unknown, including the elastic properties and composition of 20 its core (29). 21

waves (ScS) reported a core radius of 1, 830 ± 40 km (11), at the upper bound of pre-landing estimates (e.g. 13–16, 18, 30–34). ²⁴ These results are compatible with the independent findings of InSight's Rotation and Interior Structure Experiment (RISE) ²⁶ (35), which has measured the effect of the liquid core on the nutation of Mars (36). The inferred core radius and simultane-²⁷

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.

²² Initial seismic observations using core-reflected seismic

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ous estimation of a relatively low core density has motivated 29 questions about its composition: if only sulfur is considered as 30 an alloying element, an implausibly high core sulfur fraction 31 is required to match the core density whilst satisfying con-32 33 straints on mass, moment of inertia, and tidal response of the 34 planet (11). Though the observation of seismic waves reflected from Mars' CMB has helped constrain the core radius, and 35 geophysical and cosmochemical inversions have sought to infer 36 its average density and composition (e.g. 37), observations of 37 seismic waves that directly probe core properties have been 38 lacking to date. 39

Seismological investigations of core-transiting waves have 40 been made on Earth for more than a century (38, 39), where 41 both seismometers and hypocenters of large earthquakes are 42 distributed around the globe. Analyses of their travel times 43 have constrained the seismic properties of the liquid outer-44 core (e.g. 40, 41), supporting the presence of light elements 45 (42), and enabling the estimation of its equation of state (e.g. 46 43). With just a single broadband seismometer and seismic 47 sources smaller than those routinely detected on the Earth, 48 comparable observations have proved more challenging on 49 Mars. Here, we present and analyze the implications of new 50 observations, which constitute the first detection of seismic 51 waves transiting the Martian core. 52

Observations and Analysis 53

The events. The InSight mission deployed a very broadband 54 seismometer (44) onto the surface of Mars in late 2018, leading 55 to the identification of numerous seismic events (45-48). To 56 date, only two seismic events have been identified as located 57 on the opposite hemisphere of Mars to the InSight lander (49). 58 59 These events (Fig. 1 A) are designated S0976a and S1000a, corresponding to the first seismic events detected on Sols 60 (InSight Martian mission days) 976 and 1000, respectively. 61 These events were located using phases identified as PP and 62 SS – waves which travel down to a depth of nearly 1200 km 63 in the Martian mantle, and reflect from the surface of Mars 64 mid-way along their path. The Mars Quake Service (MQS) 65 estimated the epicentral distances of S0976a and S1000a to be 66 $146^{\circ} \pm 7^{\circ}$ and $128^{\circ} \pm 19^{\circ}$, respectively, with Mars-calibrated 67 magnitudes (50) M_w^{Ma} of 4.2 and 4.1, respectively (47, 49). 68 Uncertainty on marsquake locations is considerable, because 69 they depend on seismic models of Mars' layered crust and 70 71 mantle and, for source depth determination, the unequivocal 72 identification of depth phases (e.g. 7, 8). Fortunately, orbital imaging combined with data from InSight revealed S1000a to 73 74 be an impact at a distance of 125.9° and a backazimuth of $\sim 34^{\circ}$ (51), though the exact time of the impact is not known. 75 We are therefore able to precisely locate the source of S1000a, 76 and fix its depth to zero, removing this source of uncertainty 77 from our work. 78

Phase detection. At the distances corresponding to S0976a 79 and S1000a, SKS, which travels as a shear wave in the crust 80 and mantle and as a compressional wave in the core (Fig. 1 81 A), will be the first core-transiting phase to arrive (Supp. 82 Fig. S11). Core phase PKP, which travels its entire path as a 83 compressional wave, is not predicted at these distances, as the 84 expected velocities of the core and mantle require PKP arrivals 85 to be confined to areas close to the antipode of a marsquake, 86 unlike the wider detection zone on Earth. 87

SKS arrives between the PP and SS signals (Figs. 1B) and 88 with an amplitude comparable to that of PP on the radial 89 component seismograms (Supp. Figs. S15, S16). 'Radial' is 90 defined as the horizontal direction along the great circle path 91 from the event to the station, and is perpendicular to the 92 'transverse' (horizontal) component and the vertical compo-93 nent. At the distances corresponding to S0976a and S1000a, 94 SKS has key distinctive attributes that we exploit to facilitate 95 its detection: SKS should be a vertically-polarized shear wave 96 (SV) with little horizontal shear (SH) motion on the transverse 97 component (assuming seismic anisotropy is weak); due to its 98 steep incidence angle, SV energy of SKS should be linearly 99 polarized and strongest on the radial component of motion; 100 SKS is expected to have a waveform related to the shape of SS 101 (assuming minimal complexity introduced at the SS bounce 102 point) through a Hilbert transform; SKS arrives in a time-103 window where few interfering phases should be present (travel 104 time curves are shown in Supp. Fig. S11) so that arrivals 105 detected with the correct characteristics can be assigned to be 106 SKS with reasonable confidence. Radial anisotropy, which has 107 been detected in the Martian crust (52-54), should not impact 108 these attributes of SKS unless there is an as-yet undiscovered 109 more complex anisotropic texture present. 110

Detection of SKS, and measurement of its travel time rela-111 tive to either PP or SS, is made using several different meth-112 ods. These can be broken into two categories: (i) arrival 113 detection techniques, which seek to detect wavepackets of 114 energy in the seismic record with the correct characteristics, 115 and (ii) correlation-based methods, which find the time delay 116 between different packets of energy associated with seismic 117 arrivals. Three arrival-based methods (Methods A – C) and 118 two correlation-based methods (Methods D - E) were applied 119 to the data. 120

We present here results from frequency-dependent polar-121 ization analysis (FDPA), an arrival detection technique which 122 assesses whether signals are present at a range of frequencies 123 and have the required polarization. This method (labeled 124 as Method A in this work) has previously been implemented 125 for InSight data and successfully identified the core-reflected 126 ScS phases (11) as well as the minor-arc surface waves on 127 Mars (5). Fig. 1 depicts the seismic data together with the 128 excess of total horizontally-polarized energy as compared to 129 vertically-polarized energy as a function of time since the 130 MQS PP arrival time. Glitches (i.e., non-seismic spikes in the 131 recorded data) can complicate the interpretation of seismic 132 phases on InSight data (55, 56), and have been removed (see 133 also supplementary section S2.8). 134

For event S1000a, the SKS signal is identified using the 135 FDPA method (Fig. 1 C) as the horizontally-polarized energy 136 arriving ~ 340 s after PP (Method A in Table 1). This is the 137 most coherent signal in the relevant time window.

In addition to Method A, measurements of SKS differential 139 travel times were also sought for S1000a using the four other 140 complementary methods, B – E (see Table 1 and supplemental 141 material section S2), with the two alternate arrival detection 142 methods (B & C) able to detect SKS. The three different 143 arrival detection methods (A - C) enhance slightly different 144 characteristics of the waveform, with different optimal fre-145 quency bands, and therefore find slightly different differential 146 arrival times. The two cross-correlation methods (D & E) were 147 unable to measure SKS differential travel times for S1000a. 148



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 show 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 155 method (Method A in Table 1) as the horizontally polarized 156 energy arriving ~ 310 s after PP (Fig. 1 C). In this case, the 157 two cross-correlation based methods (D & E) also found sig-158 nals identified as SKS, and one further waveform identification 159 method (B) found an SKS arrival. The final waveform identifi-160 cation technique (Method C) did not find a single observation 161 clearly identifiable as SKS, we include their estimate here for 162 completeness. The SKS-PP measurements have a range of 14 s 163 whilst the SS-SKS times have a range of 9 s. The use of the 164 cross-correlation methods provides further justification of our 165

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 170 prominent on InSight's seismic records (46, 48, 58–60). We 171 verify, using the method of (60), that the signals identified 172 as SKS for both events are not associated with excess envi-173 ronmental energy (see supplementary section S2.7). In light 174 of this analysis and the expected amplitudes of SKS (supple-175 mentary section S3.4) we conclude that our SKS detections 176 and associated travel times are robust. In this investigation, 177 it has proven vital to have 3-component recordings to ensure 178 the phase identified was indeed SKS; future missions to other 179 planetary bodies (e.g., 61) will benefit if 3-component seis-180 mometers can be employed in preference to vertical-component 181 instruments alone. 182

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 observa-183 tions are used in our inversion, with an assigned uncertainty 184 185 of 10 s. This assigned uncertainty is greater than the standard 186 deviation of the travel time picks, in order to account for other sources of uncertainty. For example, potential three-187 dimensional (3D) velocity variations in the mantle can also 188 affect differential travel times (18). We quantify these using 189 ray theoretical calculations through candidate thermochemical 190 models of Mars' interior (as in 62) and find that they are 191 comparable to the assigned observational uncertainty. 192

We can assess, using forward modeling (63), how uncer-193 tainties in the event depth and epicentral distance would 194 affect SKS differential travel times. The source depth for 195 S0976a is not well constrained, as no clear depth phases (or 196 surface waves) are identified. A standard MQS event depth 197 of 50 km is assigned to this event; changing the source depth 198 by 30 km changes the differential travel times by less than 5 s 199 (Fig. S12) as the arrival times of both SKS and the mantle 200 reference phase are affected in the same way by changing the 201 event depth. Effects are more substantial when the epicen-202 tral distance is altered – changing the epicentral distance by 203 5° modifies PP-SKS time by around 10 s, but around 30 s for 204 SS-SKS differential travel times. Thus, the uncertainty in the 205 locations of S0976a makes it challenging to accurately assess 206 the seismic velocity inside Mars' core. The known impact 207 location obviates this concern for S1000a. 208

Shear wave phase SKKS, which is reflected from the under-209 side of the CMB, and Sdiff, which diffracts along the CMB 210 (Supp. Figs. S15 and S16), are not observed for either event; 211 using current models (11) we anticipate they would both ar-212 213 rive approximately 100 s after SKS, with radial and transverse 214 polarizations, respectively. The similar travel times of these two phases are due to the very small velocity difference ex-215 pected between compressional wavespeed in Mars' uppermost 216 core and shear wavespeed in Mars' lowermost mantle, so that 217 traveling across the uppermost core or along the CMB take 218 similar amounts of time. The absence of identifiable arrivals 219 permits some possible inferences to be made about the low-220 221 ermost mantle. SKKS travels to and from the CMB with a more oblique angle than SKS; if the lowermost mantle contains 222 any partial melt (e.g. 64) SKKS would be more attenuated 223 than SKS. The absence of Sdiff may be caused by a similar 224 phenomenon. Alternatively, Sdiff is observed at relatively long 225 periods on Earth (e.g. 65), which would make it difficult to 226 detect given the range of frequencies typically usable on Mars. 227 While Pdiff has been detected (9, 49, 51), it remains the case 228 that Sdiff has not vet been observed in marsquake waveforms. 229

Core properties

We first compare our observations to predictions from the 231 InSight_KKS21_GP model (3, 6, 11). This model was created 232 with Bayesian inversions using a geophysical parameterization 233 (6, 11) and has been adapted to have a three-layer, 48 km 234 thick crust, consistent with (3, 6, 7, 56). We note (i) that 235 the P-wave velocities in this model are not constrained by 236 seismic data below a depth of 800 km (6), which means that 237 predictions of PP arrival times might be less reliable than 238 SS; and (ii) the core velocity structure in this model is not 239 seismically constrained. The observations for S0976a are close 240 to predictions for the MQS epicentral distance (within 10 s for 241 both PP-SKS and SKS-SS for an event depth of 50 km). The 242 same model predicts times for S1000a, known to be an impact 243 at a distance of 125.9° , which are within 20 s for SKS-PP 244 and 15 s for SS-SKS. The PP-SS time of S1000a is within two 245 seconds of the prediction made using InSight_KKS21_GP, 246 suggesting that the discrepancy between our observed and 247 predicted SKS times may be in part due to the lack of previous 248 seismic constraints on the elastic properties of Mars' core. 249

While a core sulfur content close to the eutectic makes the 250 formation of an inner core in Mars unlikely at temperatures 251 above $\sim 1200-1500$ K (29, 66), the detection of SKS signals 252 from S0976a and S1000a places a bound on the maximum 253 size of any Martian inner core. As SKS reaches a minimum 254 radius of ~ 750 km, we expect that an inner core, if one exists, 255 would be smaller than this radius. Further constraints on 256 the presence or absence of an inner core are expected from 257 InSight's RISE instrument (35). 258

With two events and two reference phases, there are four 259 differential travel times that must be satisfied by a reasonable 260 seismic model of Mars' interior. Relying on the crust and 261 mantle of InSight_KKS21_GP and systematically changing 262 the velocity at the CMB and core velocity gradient, we can 263 seek the properties of the core that best fit the data. Such an 264 analysis (Fig. S14) suggests that a range of core properties 265 are compatible with the observations. However, the core 266 velocity and gradient of InSight KKS21 GP do not make 267 predictions which fall close (within one standard deviation) 268 to the average SKS differential travel times. Instead, this 269 forward modeling suggests that the seismic velocity of the 270 core may be higher than in that model, while the velocity 271 gradient might be slightly lower. It would be possible to 272 take an existing model of mantle properties and simply seek 273 the core properties which best fit the SKS differential times. 274 However, such an analysis would not allow for the possibility 275 that InSight_KKS21_GP does not represent the velocities 276 of the crust and mantle accurately. Moreover, it would not 277

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

Seismic inversion. Exploiting core-transiting phases, we can 287 refine estimates of the internal properties of Mars. Indeed, 288 without core-transiting phases, the elastic properties of the 289 core can only be constrained indirectly and generally under 290 the assumption that the core is composed of an iron-sulfur 291 alloy (e.g. 14-16, 30). In (7, 8, 11), the core radius was 292 estimated using the travel times of core-reflected waves to-293 gether with geophysical data. Here we invert seismic data 294 including the relative travel times of core-transiting phases, 295 requiring that the resulting models fit the mean planetary 296 density $(3.935\pm0.0012 \text{ g/cm}^3)$ and mean normalized moment 297 of inertia of Mars (0.3634 ± 0.00006) (13). 298

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

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

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

els including their crust and mantle components are shown in supplementary Fig. S21. 340

Information on the travel times of core-transiting phases 341 has allowed us to constrain the elastic properties of the core 342 much more directly than before (compare gray and colors 343 in Fig. 2B) and, importantly, without making assumptions 344 about the composition of the core and properties of its metallic 345 alloy. Our inversion results show an expected anti-correlation 346 between core radius and density - in order to fit the mass and 347 moment of inertia constraints applied, models with a larger 348 core must have a lower core density. Assuming an EH45 model 349 to inform the mantle composition, we find core radii of 1814 km350 (interquartile range, IQR: 1804 - 1823 km) and 1799 km 351 (IQR: 1773 – 1819 km) for the geophysical and geodynamical 352 inversions. Assumptions about mantle composition affect 353 these estimates somewhat: the LF and TAY compositions 354 result in a 6 km and 15 km smaller core, while the YMD 355 composition implies the smallest core, with a median radius of 356 1779 km. Therefore, while modeling choices lead to different 357 distributions of the core radii (see the histogram on the right 358 of Fig. 2C), the medians of all distributions fall within ± 17 km 359 of each other. 360

These values can be compared to the first estimates based on ScS travel times (waves reflected from Mars' CMB) of $1830 \pm 40 \text{ km} (11)$, $1840 \pm 10 \text{ km} (37)$, $1845 \pm 25 \text{ km} (7)$, and $1773 \pm 41 \text{ km}$ 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.

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When we compare models constructed using EH45 to in-368 form mantle composition, median bulk core densities, ρ_c , are 369 6.21 g/cm^3 (IQR: $6.18 - 6.24 \text{ g/cm}^3$) and 6.25 g/cm^3 (IQR: 370 $6.18 - 6.34 \text{ g/cm}^3$ for the *geophysical* and *geodynamical* mod-371 els, respectively. These average core densities depend on 372 assumed mantle composition; for example, in the *geophysical* 373 inversions, replacing the EH45 composition model with the 374 TAY one reduces ρ_c by 0.05 g/cm³, while instead using LF in-375 creases ρ_c by 0.01 g/cm³. The largest median bulk core density 376 are obtained in the *geodynamical* inversions using the YMD 377 mantle composition ($\rho_c = 6.35 \text{ g/cm}^3$, IQR: 6.27 – 6.50 g/cm³). 378 Accounting for uncertainties due to assumptions of mantle 379 composition, the range of median core densities we obtain in 380 this study, $\rho_c = 6.16 - 6.35 \text{ g/cm}^3$, is higher than the earlier esti-381 mates of 6.0 ± 0.3 g/cm³ (11). Within uncertainty, they overlap 382 with estimates obtained by (37) and (7) of 6.15 ± 0.046 g/cm³ 383 and 6.1 ± 0.1 g/cm³, respectively, and allow us to rule out some 384 of the lighter core scenarios reported in (11). 385

The P-wave velocity at the top of the core, V_{CMB} , is 386 seismically-constrained for the first time by our observation 387 of SKS. We find that, at the CMB, the median seismic P-388 wave velocity ranges from $\sim 4.89 - 5.05$ km/s, depending on 389 assumptions of mantle composition. Using EH45 to inform 390 the mantle composition, the geophysical and geodynamical 391 models presented here have median CMB core velocities of 392 4.94 (IQR: 4.87 - 5.05 km/s) and 4.89 (IQR: 4.78 - 5.01 km/s) 393 respectively. These estimates are lower than those measured 394 for pure liquid iron (e.g. 5.14 ± 0.14 km/s at 20.5 GPa and 395 2,300 K, 72), providing a further, independent argument in 396 favor of a substantial fraction of light elements in the Martian 397 core. *Geodynamical* inversions using the seismic travel time 398 dataset of (8), but excluding the core-transiting signals, re-399



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.

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

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

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

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

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

We use the seismically-derived models presented here to 455



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%.

seek out physically-consistent core compositions for Mars. 456 Specifically, we identify the combinations of light element 457 abundances in a multi-component Fe-O-S-C-H alloy, which 458 can produce the P-wave velocity V_{CMB} and ρ_{CMB} of the core 459 alloy. Although our seismic inversions also contain informa-460 tion about K'_{S} , this parameter is less well-constrained due to 461 the aforementioned weak constraint on velocity gradient with 462 depth provided by the SKS travel times. Consequently, while 463 a subset of compositional models can reproduce the velocity 464 across the full range of core pressures, we do not limit our 465 discussion to only those core compositions. As for the light 466 element content, we invert for the fraction of S and H in the 467 core, while fixing the amount of O to that of S and mantle 468 FeO following (75), as O is incorporated in the metallic core 469 alongside S during core differentiation. Carbon also is directly 470 related to S, as it is assumed to be at the solubility limit in 471 Fe-S (76). 472

We first compare the results of our inversions with equation 473 474 of state predictions for the velocity and density of different 475 alloys with a variable light element content (Fig. 3). We see that when core properties are not informed by SKS, many 476 of the retrieved models have velocity-density combinations 477 incompatible with core-candidate liquid Fe-alloys, with seis-478 mic velocities above those of alloys with > 1 wt% hydrogen. 479 The introduction of SKS travel time constraints narrows the 480 permissible velocity-density range for the Martian core, in a 481 482 way that restricts it to a region that can be accounted for by a number of liquid iron alloys of plausible light element content. 483 Therefore, while not pointing at a specific core composition, 484 the travel times of core-transiting seismic phases provide in-485 dependent arguments in support of a volatile-rich core, as 486 put forward on the basis of cosmochemical arguments which 487 encompass the chemical and isotopic analysis of Martian mete-488 orites (e.g. 22, 23, 34, 70, 71) and core differentiation models 489 (e.g. 30, 74, 75). 490

While Fe-S and Fe-O-S alloys could provide a match to 491 the SKS-informed core models, they do so at unreasonably 492 high sulfur fractions (e.g. estimates of reasonable S fractions 493 from 30, 74, are 17-19%). Inclusion of C, even at the solubility 494 limit, only marginally reduces the sulfur fraction required. 495 However, adding hydrogen to an Fe-S-O-C alloy increases the 496 core velocity substantially, while requiring much less sulfur 497 to account for the density. The effect of varying CMB tem-498 perature and pressure is to broaden these lines, increasing 499 both the range of possible velocities for a given density by 500 ~ 100 m/s (Fig. S23) and the width of implied posterior el-501 emental abundance distributions. Finally, we note that an 502 Fe-Si alloy would produce seismically impermissible velocities 503 > 6000 m/s (77), independently reinforcing the conclusion, 504 drawn from assessments of the oxidizing conditions of Mars' 505 formation, that only a negligible amount of Si is present in 506 Mars' core (e.g. 30). 507

We now turn to the results of our compositional inversions; 508 full details of the methods used are provided in supplementary 509 sections S4.4-S4.5. We find that the assumptions made when 510 seeking to match the density and velocity of our core models 511 with compositional models are as important as the seismic 512 inversion choices, and in some cases can restrict the space of 513 allowed core velocity-density space even more tightly than the 514 SKS observations. When we use EH45 to model the Martian 515 mantle and assume that O, S, C, and H are the light elements 516 in the core, we infer core compositions that contain a median 517 of 16.5 wt% S for the $geodynamical \mbox{ models and } 15.4 \mbox{ wt% S}$ 518 for the geophysical models, with IQRs of 15.1 - 18.4 wt% and 519 14.6 - 16.3 wt% respectively. The corresponding median core 520 fractions of other light elements are 2.9 - 3.2 wt% O (IQRs 521 span 2.7 - 3.7 wt% for the two families of models), medians of 522 1.2 - 1.4 wt% C (IQRs span 1.0 - 1.5 wt%) and 0.5-0.6 wt%523 H (IQRs span 0.2 - 0.7 wt%). The S and H content of the 524 core are, as expected, anti-correlated (Fig. S24) - a core with 525 appropriate density can be achieved with either very little 526 H and a larger amount of S, or a larger fraction of H and a 527 lower amount of S. The choice to model the core as saturated 528 in C has an impact of $\sim 1 \text{ wt\%}$ on the quantities of all the 529 other light elements interpreted to be present in the core. The 530 choice of the equation of state for liquid FeH is also critical 531 for these compositional inferences. Thus we do not stress 532 precise compositional inferences but rather argue that the 533 core-traversing waves presented here are indicative of a core 534 with a high fraction of light elements. 535

Estimates of the total light element abundance of the Mar-536 tian core are largely controlled by constraints on core mass, 537 while constraints on core P-wave velocities help to discrimi-538 nate between different light-element scenarios. Using EH45 539 to inform the mantle, our compositional inversions find that 540 the Martian core contains a median of 20.3 - 21.4 wt% total 541 light elements (IQRs span 19.5 - 23.4 wt%) for the *geophysical* 542 and *qeodynamical* models. This is higher by about $\sim 1 \text{ wt\%}$ 543 than the total light element composition one would obtain 544 without SKS travel time data. When considering alternative 545 mantle compositions to EH45 (LF, TAY or YMD) and result-546 ing mineralogies, median total light element abundances are 547 only affected by <1 wt%, with the LF composition suggesting 548 the smallest (median of 19.8 wt%) and the YMD composition 549 implying the largest (median of 21.6 wt%) total light element 550 abundances. 551



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 met layer is shown in red.

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

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

Conclusions

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

Materials and Methods

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

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

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