GEOPHYSICAL AND COSMOCHEMICAL EVIDENCE FOR A VOLATILE-RICH MARS. A. Khan[1], P. Sossi[2], C. Liebske[2], A. Rivoldini[3], D. Giardini[1], [1]Institute of Geophysics, ETH Zurich, Switzerland (amir.khan@erdw.ethz.ch), [2]Institute of Geochemistry and Petrology, ETH Zurich, Switzerland, [3]Royal Observatory Belgium, Brussels, Belgium.

Introduction: Constraints on the composition of Mars principally derive from chemical analyses of a set of Martian meteorites that rely either on determinations of their refractory element abundances or isotopic compositions. Both approaches, however, lead to models of Mars that are unable to self-consistently explain major element chemistry and match its observed geophysical properties, unless ad hoc adjustments to key parameters, namely, bulk Fe/Si ratio, core composition, and/or core size are made [1,2]. Here, we combine geophysical observations, including high-quality seismic data acquired with the InSight mission, with a cosmochemical model to constrain the composition of Mars.

Method of analysis: We employ the InSight seismic data, including a set of geophysical observations (tidal response, mean planetary density and moment of inertia) that sense the large-scale structure of Mars, to determine mantle and core composition. For this, we rely on a geophysical parameterization that provides a unified description of mantle and core phase equilibria and physical properties as a function of composition, temperature, and pressure. Based on the geophysically-determined mantle compositions and mean core properties (radius and density), we employ a cosmochemical approach by focusing on major elements and the extant correlation between Fe/Si and Fe/Mg that is observed in planetary materials [3]. Quantitative comparison of the geophysical and cosmochemical compositions enables us to further restrict the mantle composition of Mars by considering only those compositions that fit both constraints. Finally, we employ the jointly-predicted mantle composition to place constraints on the identities and abundances of light elements in the Martian core. The novelty of our approach lies in the inversion of multiple geophysical observations to derive physically-credible solutions of the interior state of Mars, in conjunction with cosmochemically-plausible bulk chemical compositions [4].

Results: Detailed results are presented in [4]. Here we briefly summarise the main findings. **Mantle composition:** Inverted mantle compositions in the form of major element distributions (we focus on the oxides of Fe, Mg, and Si), core properties (radius and mean density), and mantle potential temperature are shown in Fig. 1. The minor elements (Al, Ca and Na) are also varied but the geophysical data are less sensitive to variation in their abundances. From the major element distributions (Fig. 1a), we make the following observations: 1) mantle FeO content varies in the range 12.5–15 wt%; 2) a lower mantle FeO content generally correlates with a lower MgO and higher SiO_2 content. From the inverted core properties (Fig. 1b), we see that 3) a higher mean core density correlates, as expected, with a smaller core radius; and 4) the inverted core radii and mean core densities span the ranges from 1790 km to 1870 km and 6-6.3 g/m^3, respectively. The radius range of the liquid core found here is largely consistent with that obtained by [5] of 1790–1870 km (see inset Fig. 1b), whereas the present core density range covers and extends the upper part of the range found in [5] of 5.7-6.3 g/m^3, as a consequence of the lower mantle FeO content of the mantle in the present models relative to those considered in [5].

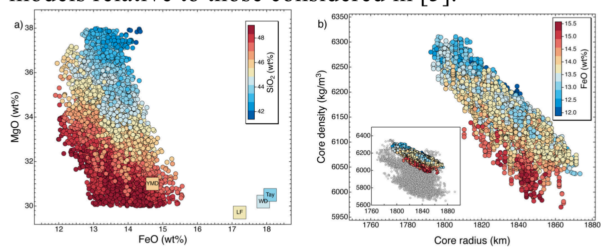

Figure 1: Inverted mantle compositions and core properties. (a) FeO, MgO, and SiO_2 distributions obtained from inversion of geophysical data. Squares indicate earlier bulk mantle compositions. (b) Mean core density as a function of core radius and mantle FeO content. Inset shows comparison with the results from [S21] *(grey circles).*

The geophysical and cosmochemical models shown in Fig. 2 represent two independent estimates of the composition of the Martian mantle and core. In order to garner more precise estimates that are compatible with both models, we construct matrices containing both the synthetic and geophysically-inverted mantle compositions of the five major oxides to quantitatively assess the mean misfit of the geophysical compositions from their cosmochemical counterparts. The FeO content is ∼1 wt% lower than that derived by [6] and the MgO content almost 2 wt% higher. Together, they yield an Mg# of the Martian mantle of 81±0.5, consistent with petrologically-derived estimates (cf. [7]). The principal differences in the Martian mantle composition compared with that of [6] can be ascribed to the fact that we adopt the much larger core mass of 0.25 (core radius of 1840 km) compared to that used in [6] of 0.18 (core radius of 1580 km). Accordingly, our estimates for the FeO content of the Martian mantle are lower, and those for MgO contents higher, than [6] in order to satisfy Mars' moment of inertia, Love number, and larger core mass evidenced by seismic reflections occurring at ~1540 km below the Martian surface as recorded by the InSight mission [5].

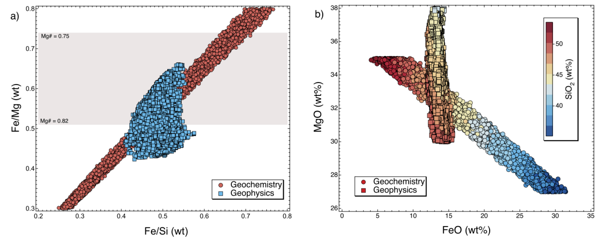

Figure 2: Comparison of geophysical and cosmochemical model compositions. (a) Distribution of Fe/Mg versus Fe/Si (wt) for the geophysically-inverted compositions and the predicted compositions from the cosmochemical model (based on 10000 model predictions). (b) Same as (a) but for MgO, FeO, and SiO_2.

Implications for core composition: We generated a set of 10^4 core composition models by randomly varying abundances of Fe (including Ni and Co), S, C, O, and H. The sum of Fe+Ni+Co was varied within the geophysically and cosmochemically allowed range (80–93 wt%), whereas C, O, and H were limited to: 0–4 wt%, 0–3 wt%, and 0–2.5 wt%, respectively. Finally, S was determined from the condition S=100–X, where X = (Fe+Ni+Co+C+O+H). Within this S range, we considered the subset covering 3-11 wt%. The resultant core compositions were then converted to mean densities based on thermodynamic solution models constructed from experimental data [4]. From the resultant core compositions, we observe that density decreases almost linearly with increasing C content; relative to C, density is much less affected by variations in the abundance of O; for given C and O abundances, density decreases with increasing amounts of S, as expected; density is most strongly influenced by the abundance of H. We find that core compositions with S ≈ 9 wt%, C ≥ 3 wt%, O ≤ 2.5 wt%, and H ≤ 0.5 wt%, are compatible with the upper range of the geophysically-determined mean core density. This supports the notion that Mars is volatile-rich [8].

Summary: With the acquisition of seismic data from Mars, we are now able to directly probe the interior of Mars from its surface. On the basis of direct and surface- and core-reflected seismic phases, in combination with a set of global geophysical data and a cosmochemical approach that focuses on major elements and the extant correlation between Fe/Si and Fe/Mg that is observed in planetary materials, we have been able to obtain a self-consistent estimate for the composition of Mars. The new mantle composition contains markedly less FeO than the canonical models of Dreibus and Wänke and others. The core of Mars must contain a substantial complement of light elements to match the observed mean core density. Based on geochemical arguments, the most plausible are, in order of abundance by weight, S (≈9 %), C (≥3%), O (≤2.5%), and H (≤0.5%).

References: [1] Khan et al., J. Geophys. Res., 2018. [2] Liebske and Khan, Icarus, 2019. [3] Yoshizaki and McDonough, Geochim. Cosmochim. Acta, 2020. [4] Khan et al., Earth Planet. Sci. Lett., 2022. [5] Stähler et al., Science, 2021. [6] Yoshizaki and McDonough, Geochemistry, 2021. [7] Agee and Draper, Earth Planet. Sci. Lett., 2004. [8] Wänke and Dreibus, Philos. Trans. R. Soc. Lond., 1994.