COME-IN

Constraining Mercury's Interior structure and evolution

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SUMMARY

Context and objectives

Mercury has long been the least known of the terrestrial planets. Only two spacecraft have so far visited Mercury. Mariner10 flew by Mercury on three occasions in 1974-1975 and MESSENGER (MErcury Surface, Space ENvironment, GEochemistry and Ranging) orbited Mercury between 18 March 2011 and 30 April 2015. With the wealth of data gathered by the NASA MESSENGER spacecraft and the ESA/JAXA BepiColombo mission launched on 20 October 2018 and on schedule for Mercury orbit insertion in December 2025, the focus of the planetary science community on Mercury is stronger than ever. One of the primary goals of these missions and of many theoretical, observational, and experimental studies is to gain a deeper understanding of the interior structure and evolution of this smallest terrestrial planet.

Spacecraft measurements alone, however, are not sufficient to reach this goal. The scarce knowledge of the high-pressure behaviour of putative bulk Mercury chemical compositions is a major problem for interpreting spacecraft measurements. As a result, studies on Mercury's interior have had to either simplify interior property models, or use thermodynamic models to predict interior mineralogy based on experiments performed at conditions of pressure, temperature, composition, and oxygen fugacity far outside those invoked for Mercury. Additional data and insight are therefore needed on the behaviour of planetary materials at relevant conditions.

With COME-IN we aimed at advancing our understanding of Mercury by integrating complementary approaches from igneous petrology, high-pressure mineral physics, computational materials science, geodesy, and geodynamics in addition to using the constraints set by recent observational data. To reach our goal, a set of specific objectives was identified building upon the complementary expertise of the five partners. They are related to the primordial structure of Mercury after accretion, magmatic processes relevant to the differentiation and evolution of Mercury, the characterization of the physical properties and structure of the iron-rich core, and to the global interior structure and thermal evolution of Mercury.

Results

We describe the main results of the COME-IN project organized according to the four principal research themes.

Primordial silicate metal equilibration

We experimentally studied the metal-silicate and sulfide-silicate partitioning behaviour of trace elements in reduced silicate melts over a wide range of S contents as a function of redox state at a pressure of 1 GPa and temperatures in the range 1833–1883 K. It was found that at conditions more reducing than $\Delta W = -3$ to -4, the metal-silicate partitioning behaviour of the majority of the siderophile elements deviates significantly from their behaviour at the valence state(s) at more oxidized conditions. These new results provide an extensive experimental foundation for studies of Mercury's differentiation under (highly) reduced conditions, which we started to perform.

We also investigated the likeliness of the existence of an iron sulfide layer at the core-mantle boundary of Mercury by comparing new chemical surface data, obtained by the X-ray Spectrometer onboard the MESSENGER spacecraft, with geochemical models supported by

high-pressure experiments under reducing conditions. We built a new data set consisting of 233 Ti/Si measurements. Multiphase equilibria experiments showed that at the conditions of Mercury's core formation, Ti is chalcophile but not siderophile, making Ti a useful tracer of sulfide melt formation. By comparing the model results and surface elemental data we showed that Mercury most likely does not have a FeS layer, and in case it would have one, it would only be a few kilometers thick (<13 km). We also showed that Mercury's metallic Fe(Si) core cannot contain more than $\sim$ 1.5 wt% sulfur and that the formation of the core under reducing conditions is responsible for the only slightly subchondritic Ti/Al ratio of Mercury's surface.

Mantle-crust evolution

The MESSENGER spacecraft provided geochemical data for surface rocks on Mercury. We used the major element composition of these lavas to constrain melting conditions and residual mantle sources on Mercury. Surface basalts have been shown to be produced by 10 to 50% partial melting of variably enriched lherzolitic mantle sources. The average melting degree is lower for the young northern volcanic planes (NVP, 0.27 ± 0.04) than for the older intercrater planes and heavily cratered terranes (IcP-HCT, 0.46 ± 0.02), indicating that melt productivity decreased with time. The mantle potential temperature required to form Mercurian lavas and the initial depth of melting also decrease from the older High-Mg IcP-HCT terrane (1650 °C and 360 km) to the younger lavas covering the NVP regions (1410 °C and 160 km). This evolution suggests strong secular cooling of Mercury's mantle between 4.2 and 3.7 Ga ago and explains why very little magmatic activity occurred after 3.7 Ga.

We also experimentally investigated the phase equilibria of five S-free compositions. Experiments were performed from 1,480 to 1,100 °C at 1 kbar under reducing conditions similar to those of Mercury’s mantle. We found a common crystallization sequence consisting of olivine, plagioclase, pyroxenes and tridymite for all magmas tested. Combining the experimental results with geochemical mapping, we identified several mineralogical provinces: the Northern Volcanic Plains and Smooth Plains, dominated by plagioclase, the High-Mg province, strongly dominated by forsterite, and the Intermediate Plains, comprised of forsterite, plagioclase and enstatite. This implies a temporal evolution of the mineralogy from the oldest lavas, dominated by mafic minerals, to the youngest lavas, dominated by plagioclase, consistent with progressive shallowing and decreasing degree of mantle melting over time.

We calculated the thickness of the crust taking into account lateral variations of crustal density. We show that the local thickness is correlated with the degree of mantle melting required to produce surface rocks. Low-degree melting of the mantle below the Northern Volcanic Plains produced a thin crust (19 ± 3 km) while the highest melting degree in the ancient High-Mg region produced the thickest crust (50 ± 12 km), disproving the hypothesis of mantle excavation by a large impact in that region.

Core structure

The seismic velocity (VP) and density of Fe-Si liquid metals at high temperatures (1400-1900 K) and high pressure (2-6 GPa), relevant for Mercury’ core, were measured in two separate experimental campaigns in Chicago, Illinois, USA and Grenoble, France. The density measurements of Fe-Si metallic liquids show that Si significantly reduces the density of Fe-rich metallic liquids. The VP measurements show that Si significantly increases the VP of Fe-rich liquid metal. This effect of Si contrasts with the retarding influence of S on the VP of Fe-rich liquids in the examined pressures range (2-6 GPa) that was reported by other experimental studies (e.g. Nishida, 2013; Jing et al., 2014). Preliminary results indicate that seismic data can help distinguishing between Fe-S and Fe-Si in Mercury’s core.

A model based on energy and entropy budgets was developed to study under which conditions the core of Mercury can maintain a dynamo up to present. Silicon in the core results in significantly larger amounts of latent heat generated upon Fe-Si freezing compared to sulfur and makes dynamo action possible during the whole evolution of the core. Dynamo action can also be extended to the present day if radioactive elements are present in the core with an

abundance of at least about one tenth of the crustal abundance or if light element exsolution out of the core is a continuously ongoing process.
We developed three different thermal evolution models for the core that take into account the possible presence of a stably stratified layer at the top of the core. The existence of such a layer is suggested by thermal evolution models and can help explaining the observed magnetic field. We showed that the existence of a stratified layer makes more entropy available for the dynamo.
We developed a thermodynamic consistent model for Fe-Ni-S liquids that includes the non-ideal mixing of Fe-S alloys and agrees with recent laboratory experiments of the density and acoustic velocity of these alloys. It shows that Mercury assuming a Fe-S core would require more sulfur in the core than in previous models.
We performed ab initio calculations of the acoustic anisotropy at high pressures and high temperatures of hcp crystals with stacking faults. The results show that an aggregate of random close-packed iron crystals, aligned predominantly North-South is consistent with the observed seismic anisotropy in the Earth's inner core.
Models of the interior and evolution
We developed a model for the obliquity of Mercury that takes into account variations in obliquity and the deviation with respect to coplanarity induced by the slow precession of the pericenter. We showed that those effects must be taken into account when determining the polar moment of inertia from the observed obliquity with the expected BepiColombo precision. We also showed that tidal effects on obliquity put a lower bound on tidal dissipation.
We interpreted the recent (2019) new estimates of the moment of inertia and tidal Love number in terms of Mercury's interior structure based on our interior structure models. Our results show that at 1 sigma Fe-S models have a core radius that is within 1972 km and 2000 km whereas for Fe-Si models the core can be about 20 km larger. The inner core radius is below 1500 km (at 3 sigma) for Fe-S models and between 1306 km and 2007 km for a Fe-Si core.
We demonstrated that taking into account a stratified outer core layer leads to higher temperatures of Mercury's mantle and outer core compared to treating the core as a convecting region with its energy distribution fixed by an adiabat. As a consequence, sulfur, which lowers the core melting temperature more drastically than silicon is not a necessary ingredient of Mercury's Fe-rich core for maintaining it partially liquid until the present. We showed that core convection and present-day dynamo action can be driven by bottom up solidification of an Fe-Si core, while having an upper liquid core layer thermally stratified.
We performed impact calculations and showed that the hemispherical asymmetry of ancient large craters on Mercury can be produced by impacting on Mercury in a formerly synchronous rotation (1:1 spin-orbit resonance) or a former 2:1 spin-orbit resonance. This asymmetry cannot be generated by impacting in the present-day 3:2 spin-orbit resonance. We concluded that Mercury previously likely had a different stable rotational state during the heavy bombardment and that the impactor that caused the Caloris basin is a feasible candidate to have initiated a transition from the former to the present-day rotational state of Mercury.

Keywords: terrestrial planets, Mercury, interior structure, petrology, geophysics