EXPERIMENTAL CONSTRAINTS ON THE STATE OF MERCURY'S CORE

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Introduction: In the absence of seismological data from Mercury little is known directly about its core. Recent Earth-based radar measurements of Mercury's rotation led to discovery of a relatively large physical libration, implying that Mercury's core is at least partially molten [1]. Notably, the existence of a global magnetic field is consistent with a convection driven dynamo in a liquid outer core. Operation of the dynamo seems to require a liquid layer of a thickness at least 4% of the core radius [2,3] and models of Mercury's thermal evolution constrained by inferences of limited radial contraction, as recorded in lobate scarps, suggest a molten layer with a thickness more than 50% of the core's radius [4].

An iron or iron-nickel core to the planet, initially molten, would have cooled and solidified by the present day, unless a volatile element (e.g. sulfur) is alloyed with the iron to reduce its freezing temperature [5]. In order to better understand the current state of Mercury's core, we investigate the melting behavior of the iron-sulfur (Fe-S) binary at corresponding pressures.

Experimental Methods: Using a 1000 US ton Walker-type multi-anvil apparatus, we measured the liquidus curves of the Fe rich portions of the Fe-S system at 10 and 14 GPa. Stoichiometric mixtures of Fe and FeS were dried and packed into MgO capsules (Fig. 1). High temperature was generated using a cylindrical rhenium furnace and monitored using a rhenium-tungsten thermocouple, without considering the pressure effect on the electro-motive force (emf). Pressure was calibrated from known phase transitions in Bi, ZnS, GaP at room temperature and in SiO_2, $CaGeO_3$ and $MgSiO_3$ at high temperatures.

In each experiment, the assembly was compressed to the target pressure at room temperature and then heated to the target temperature. After equilibrating at high pressure and high temperature, the sample was quenched by shutting off the power to the furnace. Recovered samples were polished, carbon-coated, and analyzed using a Scanning Electron Microscope (SEM) and an Electron Probe Microanalyzer (EPMA).

Results and Discussions: Table 1 summarizes the experimental conditions and the composition of coexisting solid iron and molten iron-sulfur alloy in the run products. Fig. 2 is a back-scattered electron image of a typical run product. The liquidus curves of Fe-rich alloys at 10 and 14 GPa are constructed on the basis of our experimental data and existing data on the melting temperatures of iron and the eutectic temperatures of the Fe-S binary [6,7]. The shape of liquidus curve reflects the nature of interactions between end-member components in a solution. As shown in Fig. 3, the curve at 10 GPa is relatively smooth, consistent with

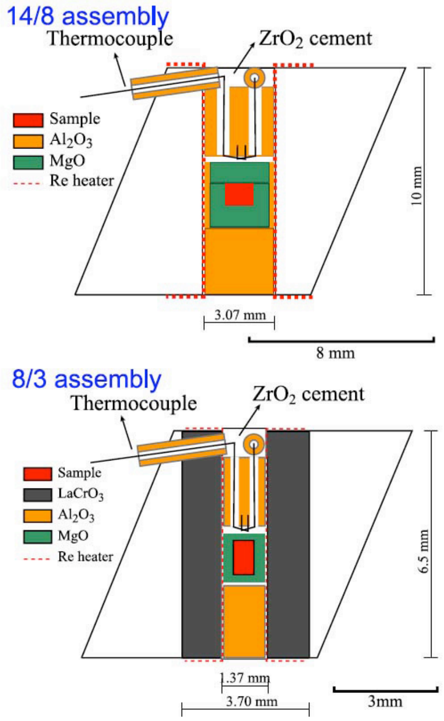

Figure 1 Cell configurations of multi-anvil experiments at 10 GPa (14/8 assembly) and 14 GPa (8/3 assembly).

Table 1 Experimental data at 10 and 14 GPa.

P (GPa)	***T*** (K)	**S in liquid** (wt. %)	**S in solid** (wt. %)
10	1273	19.0 (.4)	0.2 (.1)
10	1373	17.7 (.4)	0.2 (.1)
10	1473	16.9 (.4)	0.1 (.1)
10	1573	13.8 (.6)	0.2 (.1)
10	1673	12.0 (.4)	0.2 (.1)
10	1773	9.8 (.4)	0.2 (.1)
10	1873	7.1 (.5)	N/A
14	1400	16.0 (.8)	0.3 (.1)
14	1600	12.6 (.7)	N/A
14	1723	5.7 (1.0)	0.2 (.1)
14	1873	2.8 (.8)	0.1 (.1)

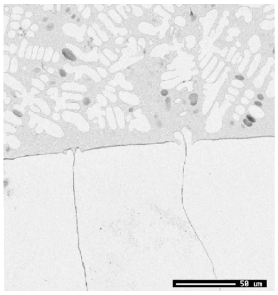

Figure 2 Back-scattered electron image of the sample recovered from run 039 (10 GPa, 1673 K), showing the boundary between coexisting solid iron and an iron-sulfur liquid with a dendritic texture.

nearly ideal mixing in the liquid. The curve at 14 GPa contains two inflection points, revealing a positive departure from ideal solution behavior.

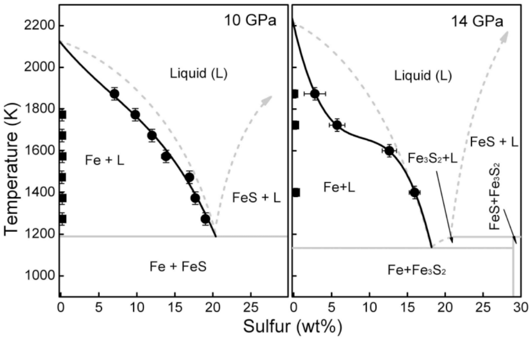

Figure 3 Phase relations in the Fe-rich portion of the Fe-S binary, showing a nearly ideal liquidus curve at 10 GPa (left plot) and a positive departure from ideal solution behavior at 14 GPa (right plot), indicated by the two inflection points on the liquidus curve. The curves are polynomial fits to our experimental data on coexisting liquid (circles) and solid (squares) at various temperatures. Approximate ideal liquidus curves (dashed gray) [7] are shown for comparison. Uncertainty in temperature is estimated as ±30 K. Uncertainties in sulfur contents are one standard deviations of multiple analyses.

The non-ideality at 14 GPa leads to substantial reductions in the liquidus temperatures of Fe-rich alloys (Fig. 2). These results have direct implications for understanding the nature and evolution of Mercury's core. The sulfur content of Mercury's core is poorly constrained. In applying our data to Mercury, we consider a wide range of composition from a sulfur-free core to a fully molten core containing 12 wt% sulfur. With the estimated present-day temperature at the CMB between 1700 and 1900 K, we find three possible core states at the present time: a Ganymede-like state [9], an Earth-like state, and a double-snow state. The Ganymede-like state with a single snow zone and a solid inner core is applicable over a wide range of sulfur contents and present-day temperatures at the CMB. The radius of the inner core is determined by the core's sulfur content and temperature. If the sulfur content is below 4 wt%, the solid inner core would occupy more than 50% of the core's radius. Such a large inner core may not be compatible with the observation of limited contraction on the planet [4]. For only a few specific combinations of sulfur content in the core and current temperature at the CMB, Mercury's core would be in the Earth-like state, with iron precipitating at the ICB. The double-snow state is the most likely state if Mercury is at an early stage of inner core growth, with the inner core radius below about 1200 km. The present-day core would consist of two distinct zones of iron snow formation in a layered outer liquid core and possibly a small solid inner core.

The inferred double-snow state of Mercury may be unique among the terrestrial planets and terrestrial-like satellites with iron-sulfur cores, as it results from the simultaneous presence of two segments in the core where the liquidus temperature gradient is negative or shallower than the adiabatic temperature gradient. Only on Mercury do the core conditions span the pressure range over which both segments of negative or shallow liquidus gradient are present. The range is not found in less massive satellites such as the Moon (core pressure < 10 GPa) and Ganymede (core pressure < 14 GPa), and is lower than found in cores of larger planets such as Mars (core pressure > 29 GPa) and the Earth (core pressure > 136 GPa).

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