

CHEMICAL CONVECTION IN THE LUNAR CORE FROM MELTING EXPERIMENTS ON THE IRON-SULFUR SYSTEM. J. Li¹, J. Liu¹, B. Chen¹, Z. Li¹ and Y. Wang², ¹Department of Earth and Environmental Sciences, University of Michigan, 1100 N. University Ave, Ann Arbor MI 48109, USA. jackieli@umich.edu, ²Center for Advanced Radiation Sources, The University of Chicago

Introduction: By reanalyzing Apollo lunar seismograms using array-processing methods, a recent study suggests that the Moon has a solid inner core and a fluid outer core, much like the Earth [1]. The volume fraction of the lunar inner core is 38%, compared with 4% for the Earth. The pressure at the Moon's core-mantle boundary is 4.8 GPa, and that at the ICB is 5.2 GPa (Fig. 1).

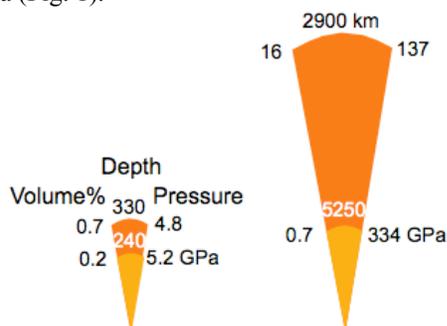


Fig. 1 The layered structure of the lunar core (left) compared with that of the Earth's core (right), showing the volume fraction of the outer and inner cores and the depths and pressures at the CMB and ICB.

The partially molten state of the lunar core provides constraints on the thermal and chemical states of the Moon: The temperature at the inner core boundary (ICB) corresponds to the liquidus of the outer core composition, and the mass fraction of the solid core allows us to infer the bulk composition of the core from an estimated thermal profile [1]. Moreover, knowledge on the extent of core solidification can be used to evaluate the role of chemical convection in the origin of early lunar core dynamo [2].

Sulfur is considered an antifreeze component in the lunar core. Here we investigate the melting behavior of the Fe-S system at the pressure conditions of the lunar core, using the multi-anvil apparatus and synchrotron and laboratory-based analytical methods. Our goal is to understand compositionally driven convection in the lunar core and assess its role in generating an internal magnetic field in the early history of the Moon.

Methods: *In situ* experiments were carried out at the Sector 13 (GSECARS) of the Advanced Photon Source, Argonne National Laboratory. A 1000-ton press with a T-25 multi-anvil module was used to generate high pressure and high temperature. A 14/8 equatorial cell assembly was designed to reduce absorption of X-rays by materials surrounding the sample, thus allowing radiographic observations. The assembly

used a graphite or titanium-boride/boron-nitride heater and replaced the center portion of the zirconia insulating sleeve with an MgO ring (Fig. 2).

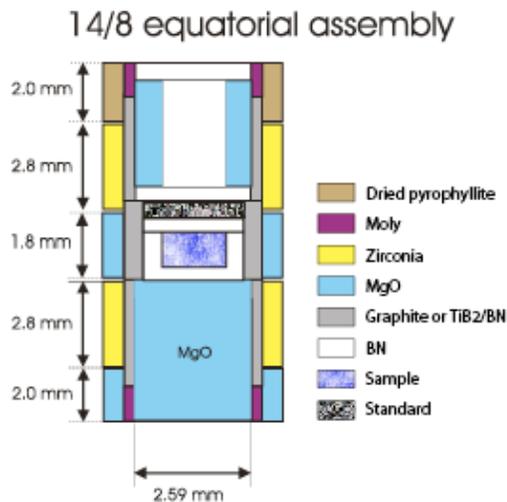


Figure 2 Multi-anvil 14/8 equatorial cell assembly for *in situ* X-ray radiography and diffraction experiments.

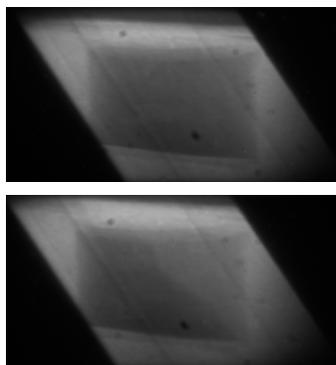
The X-ray radiographic imaging system at 13-ID-D includes a Ce-doped YAG fluorescent screen and a CoolSNAP CCD camera that records two-dimensional intensity data. The beamline is also equipped with an energy dispersive X-ray diffraction (EDXD) setup that allows *in situ* pressure determination and phase identification.

The sample consisted of a mixture of Fe and FeS powders with nine percent sulfur by weight. Thin layers of platinum and MgO powder mixture were placed above and below the sample chamber to serve as pressure markers. Temperature was monitored through a type C Re-W thermocouple. In each run, the assembly was first compressed to the target pressure, and then heated continuously until the sample is fully molten. X-ray diffraction spectra were collected at ~ 1000 K, in order to determine the pressure of the annealed sample. During heating, radiographs were recorded at 5 s time intervals to monitor the initiation and completion of the melting process. After reaching the liquidus temperature of the Fe-S starting composition, the assembly was cooled back to a temperature near the eutectic for another X-ray diffraction measurements of sample pressure, and then quenched and recovered for further analysis.

Parallel to the *in situ* experiments, we have conducted a series of melting experiments at the High

Pressure Laboratory of the University of Michigan, using a 14/8 cell assembly. Sample pressure was estimated according to a calibration curve, established on the basis of known phase boundaries in SiO_2 and CaGeO_3 . Temperature was monitored through a type C Re-W thermocouple. The assembly was first compressed and then heated to a target temperature between the eutectic and liquidus. After equilibrating for 10 to 30 min, the sample was quenched and recovered for chemical and textural analyses using an electron microprobe at the University of Michigan EMAL (Electron Microbeam Analysis Laboratory).

Results and Discussion: Two *in situ* experiments were conducted near 5 GPa pressure and up to 1673 K. In run T1259, we observed melting at 1206 K, manifested by segregation of melt from solid, forming an uneven boundary (Fig. 3). This is considered an upper bound for the eutectic temperature, as the melt-solid interface appeared between 1174 K and 1206 K. Compared with previous results at 3 GPa [3] and 6 GPa [4], the eutectic temperature at 5 GPa is about 50 K lower.



T1259_013
180 ton, 1174 K

T1259_014
180 ton, 1206 K

Figure 3 Radiographs of Run T1259 at 5 GPa. Upper: Compressed Fe-S mixture before heating; Lower: Fe-S melt (gray, right side of the rectangular-shaped sample) overlying Fe solid (dark). The sample size is roughly 0.6 mm x 1 mm.

On the basis of chemical analysis of the recovered samples from both *in situ* and quench experiments, our preliminary data suggest that the liquidus curve at 5 GPa differs from that at 6 GPa, possibly influenced by phase transitions in iron within the pressure and temperature range (Fig. 4). The difference is not surprising given the contrast in the shapes of liquidus curves between 3 and 6 GPa [3, 4].

The detailed contour of the liquidus curve constrains the thermal and chemical states of the lunar core and determines the amount of compositional buoyancy force resulting from the growth of a solid inner core. As illustrated in Fig. 4., in the simplified Fe-S binary model, the temperature at the lunar ICB is related to the sulfur content of the entire core according to the solidus and liquidus curves: Given a sulfur content, the temperature at the ICB can be determined by matching the mass fractions of the solid and liquid portions

of the core (Fig. 4, thick red curve). With the mass fractions approximated by the volume fractions of 0.38 for the liquid versus 0.62 for the solid, we find that a hot ICB at 1900 K implies ~ 3 wt.% sulfur, and a cold ICB at 1400 K corresponds to ~ 9 wt.% sulfur in the lunar core (Fig. 4, horizontal thin red lines). In the case of a sulfur-poor core, the inner core may be relatively young and further cooling by several hundreds of degrees is allowed before the core solidifies completely. A sulfur-rich core likely has an older inner sphere and would freeze up when the Moon cools by additional couple of hundred degrees.

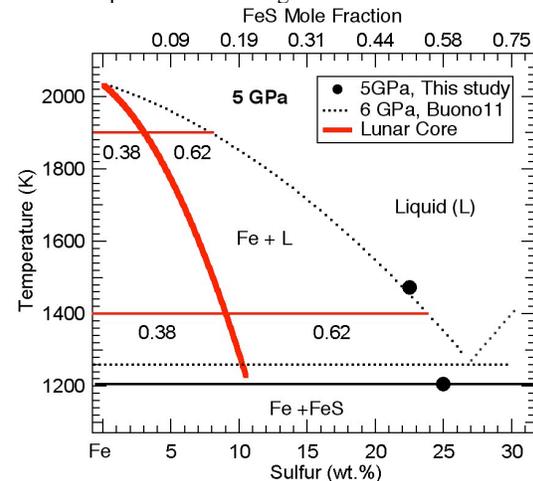


Figure 4 Iron-sulfur binary phase diagram and temperature-composition relation in the lunar core. Solid circles are data from this study. Dotted line and curves are after [4]. See text for details.

The chemical buoyancy force scales with the slope of the liquidus curve at the ICB temperature. At the high temperature segment of the liquidus, the amount of sulfur in the liquid changes by 4 wt.% per 100 K. The rate of change drops to 2 wt.% sulfur per 100 K near the eutectic temperature. It follows that the role of chemical convection may have diminished considerably over the history of the Moon, if the lunar core contains a large amount of sulfur. On the other hand, if the lunar core is sulfur poor, the role of chemical convection was probably negligible in the early history of the Moon and would have remained nearly constant since the inception of the inner core.

References: [1] Weber R. C. et al. (2011) *Science*, 331, 309–312. [2] Stegman D. R. et al. (2003) *Nature*, 421, 143–146. [3] Ryzhenko B. and Kennedy G. C. (1973) *Am. J. Sci.* 273, 803–810. [4] Buono A. et al. (2011) *GCA*, 75, 2072–2087.

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