Highlights & Breakthroughs contribution for American Mineralogist on “Liquid properties in the Fe-FeS system under moderate pressure: tool box to model small planetary cores” by Guillaume Morard et al.

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The interpretation of seismic and magnetic field observations used to probe the deep interior of terrestrial bodies such as the Earth or the Moon requires understanding the physical and chemical properties of metallic cores. This necessary knowledge comes essentially from high-pressure experimental studies and *ab initio* calculations on core analogues in the solid and the liquid states as well as from thermal modeling of the deep interior. In particular, density, when combined with seismic velocities of iron alloys as presented by Morard and coworkers, can be used to place constraints on core chemistry, elastic constants, as well as on the size of the core and thus, allows probing core structure and dynamics.

Morard and coworkers conducted density experiments on liquid samples in the Fe-FeS system. The exact chemistry of terrestrial cores is not presently known and the amount and nature of elements lighter than iron present in the core is debated and varies for each body. However, the Fe-FeS system is considered to be a relevant core analogue of terrestrial bodies, due to the presence of sulfur in iron meteorites, as evidenced by meteorite geochemistry (e.g., Dreibus and Wänke, 1985) and siderophile behavior of sulfur over a wide pressure range, as demonstrated by solubility experiments (e.g., Tsuno et al., 2011). The physical properties of Fe-

S alloys at conditions relevant to planetary cores are still largely unconstrained, especially in the liquid state where *in situ* measurements are technically challenging. As pointed out by Morard and coworkers, the available dataset of liquid Fe-S density is meager under pressure and more concerning, previous density studies in the Fe-FeS system lack consensus, with differences in density being as high as >500 kg/m^3 for identical compositions at similar pressure and temperature conditions. Temperature differences, pressure calibration, and sample contamination could be some of the many factors that can bias experimental data.

As a result, the current experimental density dataset prevents from understanding the chemistry-dependence of the density of Fe-S liquids. To tackle this issue, Morard and coworkers conducted a systematic study of the effect of sulfur content on the density of Fe-S liquids. The authors investigated the density and structure of Fe-S liquids containing between 9.9 and 50 at.% S using experiments under pressure (up to 5.2 GPa) and high temperature (1600-1980 K) as well as *ab initio* calculations at comparable conditions. Based on their experimental measurements and theoretical calculations, equations of state (EoS) were developed in order to model density and sound velocity as a function of depth, temperature, and sulfur content.

What Morard and coworkers provided through their work is not just a new set of density data of iron alloys, but a coherent density-sound velocity model for small terrestrial cores as a function of pressure, temperature, and sulfur content. This model can be used to predict the structure of small planetary cores as well as interpret seismic data, and therefore has significant implications for our understanding of the present-day state of metallic cores in small terrestrial bodies and planetary cooling history.

The new density-sound velocity model presents a significant advancement in understanding the present-day composition of small terrestrial cores in the liquid state and should also motivate new experimental and numerical work, as many related questions require further research: for instance, what are the density and sound velocity of a partially solid core? The proposed model is for liquid alloys, which is necessary to understand fully liquid cores as it possibly occurred shortly after the differentiation of a telluric body. However, several terrestrial bodies are thought to currently have a non-negligible solid fraction, which likely affects both density and sound velocity. To add complexity, it should be noticed that for a given bulk density value, there is no unique solution regarding core composition and state, as different combinations of sulfur (or any other light element) content and degree of crystallization (i.e., solid fraction) can provide similar bulk density values. It is possible to use the models by Morard et al. to compute the density of partial melts, using the EOS and sound velocity for solid iron from previous studies (Tsujino et al., 2013; Antonangeli et al., 2015), though new experiments at high pressure (>5 GPa) and for other compositions than Fe-S as well as numerical modeling of the physical properties are needed to model core crystallization of terrestrial bodies other than the Moon.

Also, what is the effect of core chemistry on the generation and sustainability of an intrinsic magnetic field? In the case of the Moon, magnetic observations have suggested that a core dynamo operated for more than 500 million years (Weiss and Tikoo, 2014) and this magnetic activity was possibly linked to the thermal evolution and crystallization regime of a metallic core (e.g., Laneuville et al., 2014; Scheinberg et al., 2015). The cause for the cessation of the dynamo remains debated partly because of the lack of constraints on the core composition and crystallization regime. Assuming an Fe-S core composition and a core-mantle boundary temperature (T_{CMB}) from previous studies (Laneuville et al., 2014), Morard and coworkers' model suggests that the amount of sulfur in a fully liquid Lunar core is more than twice the one estimated as part of previous elastic data. For a core radius of about 330 km (e.g., Weber et al., 2011), the amount of S present in a fully liquid core would be about 16 wt.%. These estimates strongly depend on T_{CMB}, as lowering the T_{CMB} value requires an increase in the sulfur content in the core in order to match the mass constraint. An enrichment in sulfur would result in a decrease in the liquidus temperature (i.e., the temperature at which the first iron crystals form), affecting the timing of core crystallization and thus, the magnetic field. Interestingly, if the Fe-FeS liquidus curve and the temperature-depth curve of the core (adiabat) intersect at the top of the core (e.g., Breuer et al., 2015), the Lunar core would undergo top-down crystallization (so called "iron snow" regime) rather than bottom-up crystallization (inner core formation). The "iron snow" regime has been found to be a possible explanation to the dynamo cessation early in the history of Mars (Davies and Pommier, 2018) and it seems that it might also occur in the Moon.

By applying their results to the Moon, Morard et al. add a new level of detail to the picture of the Lunar core that has not come into focus yet. While the exact chemistry of the Lunar core is still unconstrained, it is reasonable to assume that the seismic data reflect the present-day composition of the core, its thermal state, and provide information about its cooling history. The exploration of core crystallization and magnetic activity may require the joint-investigation of multiple physical properties, such as density, thermal and electrical conductivity. New experimental and multi-disciplinary approaches may well pave the way for relating field observations from past and future spacecraft missions to the evolution of planetary interiors.

References

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