Probing planetary core structure and dynamics using density and sound velocity

ANNE POMMIER

1UCSD-SIO-IGPP, 8800 Biological Grade, La Jolla California 92093-0225, U.S.A.

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 analogs 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 et al. (this issue), 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 et al. 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 analog 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 et al., the available data set 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/m³ 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 data set prevents from understanding the chemistry-dependence of the density of Fe-S liquids. To tackle this issue, Morard et al. 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 atom% 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 to model density and sound velocity as a function of depth, 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 to this topic, 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 \(T_{\text{CMB}}\) from previous studies (Laneuville et al. 2014), Morard et al.’s 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 \(T_{\text{CMB}}\), as lowering the \(T_{\text{CMB}}\) value 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.