

SOUND VELOCITY AND EQUATION OF STATE OF IRON-SILICON AND IRON-CARBON LIQUIDS UNDER PLANETARY CORE CONDITIONS. Z. Jing¹, J. Han¹, T. Yu², and Y. Wang², ¹Department of Earth, Environmental, and Planetary Sciences, Case Western Reserve University, Cleveland, OH 44106, zhicheng.jing@case.edu, ²Center for Advanced Radiation Sources, The University of Chicago, Chicago, IL 60637.

Introduction: Silicon and carbon have been suggested as important candidates for light elements in the molten iron cores of Earth and other terrestrial planets such as Mercury (e.g. [1, 2]). The presence of light elements can significantly reduce the density and melting temperature of Fe cores. Therefore effects of light elements on physical properties of Fe liquid are critical to the understanding of the dynamics and thermal evolution of planets. In order to place constraints on abundances of light elements in planetary cores, knowledge on the equation of state (EoS) of Fe-rich liquids, which relates density to pressure, temperature, and liquid compositions, is required.

However, previous measurements on the density of Fe-rich liquids are limited in both liquid composition and pressure ranges. In addition the uncertainties in density measurements are large (2-5 %) and there exist large discrepancies between various studies. For example, the difference in the density of Fe-17wt%Si liquid at 4 GPa determined by Sanloup et al. [3], Yu and Secco [4], and Tateyama et al. [5] is as large as 6%. Thus, the EoS of Fe-rich liquids has been poorly constrained.

Compared to density, sound velocity data can provide much tighter constraints on the compressibility and its pressure derivative, and hence the equation of state of Fe-Si liquids. In this study, sound velocities of Fe-Si and Fe-C liquids were determined by combining the ultrasonic measurements with synchrotron X-ray radiography and diffraction techniques under high-pressure and temperature conditions from 0.5 to 6 GPa and 1500 to 1973 K. Combined with 1-atm density data in the literature, the high-pressure velocity data provide tight constraints on the equations of state and thermodynamic properties such as the adiabatic temperature gradient for Fe-C and Fe-Si liquids.

Experimental methods: *In-situ* sound velocity measurements at high pressures were performed by combining the ultrasonic technique and synchrotron X-ray diffraction and radiography imaging techniques using a multi-anvil high pressure device at Beamline 13-ID-D of the Advanced Photon Source (operated by GSECARS, the University of Chicago), Argonne National Laboratory. The setup for synchrotron experiments is similar to that of Jing et al. [6] and are shown in Fig. 1. Four Fe-Si compositions (Fe-10wt%Si, Fe-17wt%Si, Fe-25wt%Si, and Fe-33wt%Si) and an Fe-C composition (Fe-5wt%C) were studied.

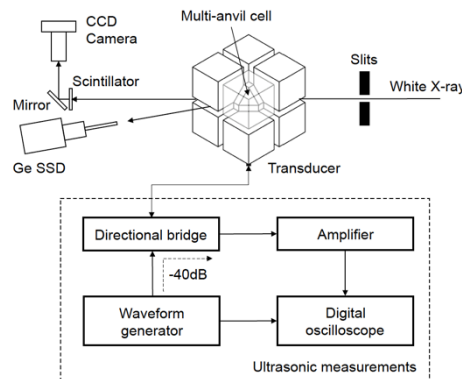


Fig. 1. Experimental setup for sound velocity measurements

High pressure was generated using a Kawai-type multi-anvil device (MA). Fig. 2 shows the cell assembly used in this study. Samples were inserted in boron nitride (BN) sleeve capsules and sandwiched by buffer rods (BR) and backing plates (BP), both made of fully densified Al_2O_3 . Both ends of the anvils, buffer rods, and backing plates were mirror polished using 1 μm diamond paste to enhance sound wave propagation and reflection.

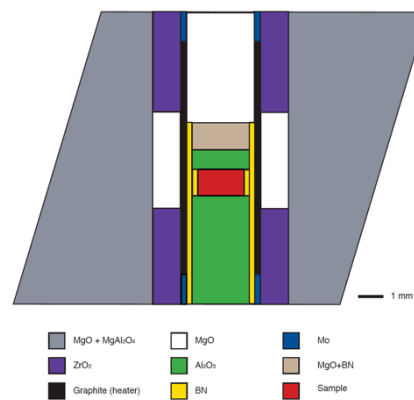


Fig. 2. Cell assembly used for sound velocity measurements

Ultrasonic sound velocities were determined using the pulse-echo method. Input signals of 40-60 MHz (3-5 cycles of sine waves) with amplitude of 1-5 V were generated by an arbitrary waveform generator and were converted to elastic waves by an LiNbO_3 piezoelectric transducer (10° Y-cut) attached to the back of the WC anvil using high temperature epoxy resin. Reflected elastic waves at the anvil-BR, BR-sample, and sample-BP interfaces were converted back to electrical signals by the same transducer and received by a digi-

tal oscilloscope. The time difference between the arrivals of the BR-sample and the sample-BP reflections gives the round-trip travel time for the sound waves propagating through the sample (Fig. 3). Sample lengths were determined from the synchrotron X-ray radiographic images, generated by a YAG scintillator and recorded by a CCD camera (Fig. 4). The sound velocities were then calculated by taking the ratios of sample lengths and travel times. Complete melting of samples was confirmed by the dramatic changes in the amplitude and travel time of the Sample-BP echo and by the disappearance of sample X-ray diffraction peaks and the appearance of diffused scattering of X-ray by the molten sample.

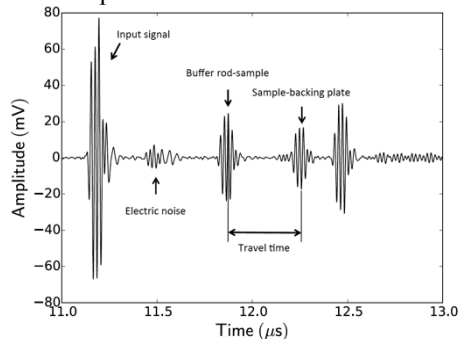


Fig. 3. Example sound wave signals received

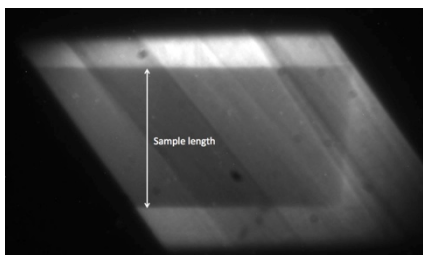


Fig. 4. Example sample X-ray radiographic image

Results and Discussion: Sound velocity data for all four Fe-Si compositions and the Fe-5wt%C composition were obtained. Figure 5 shows the results for Fe-10wt%Si as an example. Compared to our previous results on the velocity of Fe and Fe-S liquids at high pressures [6], we find that the presence of both C and Si increases the velocity of liquid Fe, in contrast to the effect of S. The measured velocities of Fe-C and Fe-Si liquids increase with compression and decrease slightly with increasing temperature.

Sound velocity data were combined with 1-atm density data to obtain the equation of state for Fe-Si and Fe-C liquids. Figure 6 compares the equations of state for Fe-Si liquids from this study (solid lines) with density data in the literature (symbols) [3, 4]. Our results are closer to those of [4].

The sound velocity data and EoS can be used to calculate other thermodynamic properties such as the Grüneisen parameter and the adiabatic temperature gradient under planetary core conditions. Such properties are important to understanding the thermal evolution of planetary cores such as the core of Mercury.

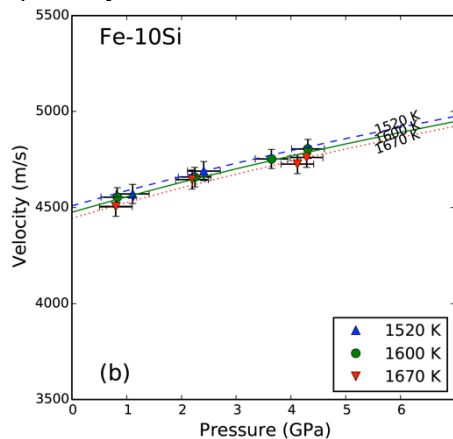


Fig. 5. Sound velocity results for Fe-10wt%Si

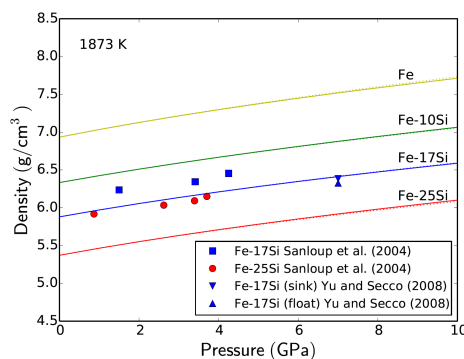


Fig. 6. Density of Fe-Si liquids at high pressures calculated using the equations of state obtained in this study.

References: [1] Li J. and Fei Y. (2003) *Treatise on Geochem.*, 2, 521-546. [2] Smith D. E. et al. (2012) *Science*, 336, 214-217. [3] Sanloup C. et al. (2004) *Geophys. Res. Lett.*, 31, L07604. [4] Yu X. and Secco R. A. (2008) *High Press. Res.*, 28, 19-28. [5] Tateyama R. et al. (2011) *Phys. Chem. Minel.*, 38, 801-807. [6] Jing Z. et al. (2014) *Earth Planet. Sci. Lett.*, 396, 78-87.

Acknowledgement: This work was supported by the National Aeronautics and Space Administration (NNX14AN01G) and the National Science Foundation (EAR-0711057, 1214376). Experiments were performed at the GSECARS beamline 13-ID-D. GSECARS is supported by the NSF EAR-0622171 and Department of Energy (DOE) DE-FG02-94ER14466. The APS is supported by DOE Office of Science, Basic Energy Sciences, Contract No. DE-AC02-06CH11357.