

Is Carbon Responsible for the Anisotropy in the Earth's Inner Core?

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The Earth's inner core is seismically anisotropic: compressional sound waves travel 3-4% faster along the spin axis than in the equatorial plane. The cause of the anisotropy has been generally attributed to preferential alignment of iron crystals. The density of the inner core is smaller than pure iron under corresponding pressure and temperature conditions, presumably due to the presence of lighter elements such as H, C, O, Si or S. In this study, we measured the compressional and shear wave velocities of Fe₃C using nuclear resonant inelastic X-ray scattering in conjunction with X-ray diffraction experiments. Our results indicate that compared to pure iron, Fe₃C provides a better match of compressional and shear wave velocities to the seismically observed values of the inner core, supporting carbon as a light element in the inner core. We observed large elastic anisotropy in Fe₃C at ambient conditions. If the anisotropy persists to the pressure and temperature conditions of the inner core, Fe₃C might help explain the observed seismic anisotropy.

Accurate determination of sound velocities in iron-rich alloys is crucial for interpreting seismic observations of the Earth's core. Nuclear resonant inelastic X-ray scattering (NRIXS) probes the vibrational properties of resonant isotopes, e.g. ⁵⁷Fe. In conjunction with X-ray diffraction measurements, which provide density and bulk modulus information, the NRIXS method can be used to measure sound velocities of iron-rich samples [1, 2]. For such experiments, an X-ray source with high energy resolution and bunched time structure is required. The Advanced Photon source (APS) is one of the few places in the world that provide such facility. Recently, an X-ray diffraction capability was integrated into the nuclear resonant scattering and laser-heating setup at sector 3-ID

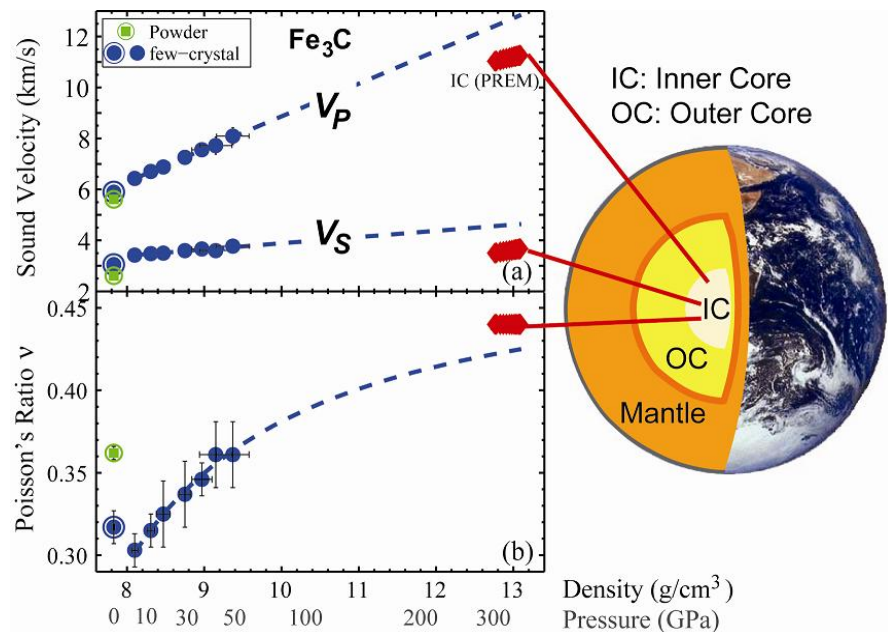


Fig. 1. (a) Compressional wave velocity (V_P) and shear wave velocity (V_S) of Fe₃C at 300 K as a function of density, which is corrected for ⁵⁷Fe enrichment. At pressures below 6 GPa, Fe₃C is magnetic (marked by outer circles). At ambient conditions, the V_P and V_S of the few-crystal sample are 5% and 16% larger than those of the powder sample, respectively, indicating strong anisotropy. (b) Poisson's ratio ν of Fe₃C as a function of density. At ambient conditions, the Poisson's ratio of the powder sample is larger and closer to the limiting value of 0.5 for liquids.

of the APS, enabling simultaneous NRIXS and X-ray

diffraction measurements. *In situ* X-ray diffraction measurements allow us to detect microscale impurities, phase transitions and chemical reactions upon compression or heating, and to obtain information on sample pressure, grain size distribution, and unit cell volume, thus providing more reliable and accurate data of sound velocities.

We conducted experiments on ^{57}Fe -enriched Fe_3C samples at room temperature. One sample consists of a few crystals with a size comparable to that of the focused X-ray beam, i.e., $\sim 10\ \mu\text{m}$. The other sample can be considered a powder sample since the crystal size is less than $3\ \mu\text{m}$, and we used unfocused X-ray beam with a diameter of $> 100\ \mu\text{m}$. We found that at ambient conditions the V_P and V_S of the few-crystal Fe_3C are 5% and 16% higher than that of the powder Fe_3C , respectively. The Poisson's ratio ν of the powder sample is 14% larger than that of the few-crystal sample, and closer to the limiting value of 0.5 for liquids (Fig. 1) [1]. These results indicate large elastic anisotropy in Fe_3C , consistent with the recent report of extreme elastic anisotropy in cementite on the basis of first-principle calculations and X-ray diffraction measurements [3, 4].

The few-crystal sample was further compressed to 50 GPa at room temperature. The V_P and V_S of this sample can be expressed as functions of density (ρ): V_P

(km/s) = $-3.99 + 1.29\rho$ (g/cm^3) and V_S (km/s) = $1.45 + 0.24\rho$ (g/cm^3) (Fig. 1) [2]. These results indicate that the addition of carbon to iron in the form of Fe_3C brings V_P and V_S of iron closer to that of the inner core [5], supporting carbon as a light element in the Earth's inner core.

If Fe_3C remains highly anisotropic under the pressure and temperature conditions of the Earth's inner core, it may be responsible for the observed seismic anisotropy. Furthermore, as the core temperature decreases over time, the liquidus phase of a carbon-bearing core may become increasingly carbon-rich. Could a variation in carbon concentration with depth explain the layered anisotropy structure of the inner core? To test this idea, we need to measure the sound velocities of Fe_3C and other iron-carbon compounds (i.e., Fe_7C_3) under simultaneous high pressures and high temperatures.

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