Understanding Why Sound Waves Travel Faster along Earth's Axis in the Inner Core

New calculations of iron's elasticity at the temperatures and pressures of Earth's inner core show that the directional dependence of sound waves in the crystals is larger than expected.

We don't know very much about Earth's inner core, the most inaccessible region of Earth. What we do know about it puzzles and intrigues us. (See the article by Raymond Jeanloz and Barbara Romanowicz in PHYSICS TODAY, August 1997, page 22.) In particular, researchers have found that compressional sound waves, generated by earthquakes on one side of the globe, arrive at different times at a point on the other side of the globe, depending on their route through Earth's inner core. When the path has a component parallel to Earth's rotational axis, the sound waves move faster than when their path takes them along an equatorial plane.[1]

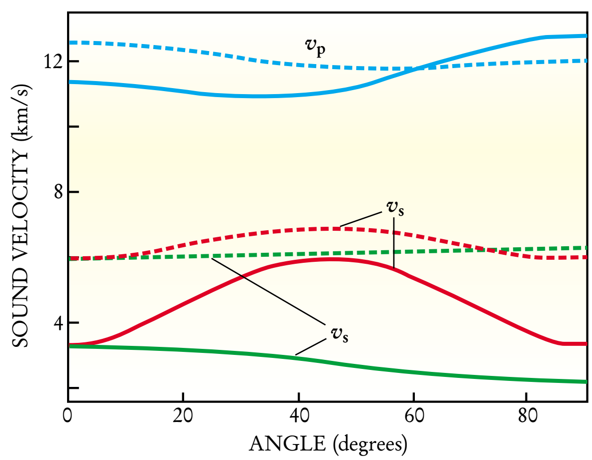
Iron crystals are the main constituent of the solid inner core. They are expected to have anisotropic elastic properties, as do most crystals, with acoustic waves traveling at different speeds in different directions. For the polycrystalline inner core to exhibit a similar anisotropy means that some or all of the single crystals are aligned with Earth's rotation axis. The crystals may have grown with a preferred orientation when the inner core was formed,[2] or processes at work in the inner core may have aligned them over time.

Why focus so much attention on what is, in fact, only a difference of a few percent in the seismic velocity in Earth's deep interior? A key reason is that understanding this phenomenon might help us learn about forces in the core. Most mechanisms for aligning the crystals invoke some kind of flow within the solid core. If different mechanisms produce different flows, then more precise seismic data might help distinguish which mechanisms are at work.

Lars Stixrude of the University of Michigan told us that "the key to future progress will be to think of ways to test different proposed flow patterns against observational evidence from seismology." In the process, researchers may gain more insight into the inner core, such as the nature of its magnetic field.

To understand better the origin of the seismic anisotropy observed in the inner core, researchers have been trying to experimentally measure and theoretically calculate the elastic properties of iron. Those are formidable challenges at the extreme conditions of the inner core, where temperatures are estimated to range up to 6000 K and pressures can bear in at more than 360 GPa.

That's why a new state-of-the-art calculation of iron's elasticity, which starts from first principles and incorporates the effects of high temperatures, is receiving considerable attention. Stixrude and Gerd Steinle-Neumann (also at Michigan) teamed up with Ronald E. Cohen (Carnegie Institution of Washington and Caltech), and Oguz Gülseren (NIST, Gaithersburg, Maryland) to find that compressional sound waves in a single crystal travel 12% faster in one direction than in the orthogonal direction at the high temperatures and pressures expected in the inner core.[3]



ANISOTROPY IN SOUND WAVES calculated for a single crystal of hexagonal close-packed iron, as a function of the angle with the *c*-axis. Calculations were done at 0 K (dashed curves) and at 6000 K (solid). The velocity of compressional waves v_p (blue curves) at 0 K is faster along the *c*-axis (0°) than at right angles to it, but that trend is reversed at the 6000 K temperature of Earth's inner core. Also shown are the speeds of shear waves, v_s, polarized in two orthogonal crystallographic directions (green and red). These waves are slower at 6000 K than at 0 K. For the shear waves polarized along the *c*-axis (green) the angle dependence of the acoustic anisotropy reverses at the higher temperature. (Adapted from ref. 3.)

With such an unexpectedly high velocity difference, the theorists estimate that only 30% of the crystallites in the inner core need to align along the rotational axis to explain the observed seismic anisotropies. A previous calculation done at low temperature found a lower single-crystal anisotropy, leading researchers to propose that nearly all the crystallites needed to line up.[4]

What might produce a preferential orientation of the crystals? Several mechanisms have been proposed, but there is no agreement yet on which is correct. The new calculations provide a useful constraint: Until the work by Steinle-Neumann and company, most workers in the field thought that the sound waves would travel more rapidly in one particular direction of the crystal (known as the *c*-axis). But, to the theorists' own surprise, things reverse at high temperatures, with sound waves then traveling more slowly in the *c* direction. Such a reversal means that any proposal for the orientation of crystallites that assumed a fast *c*-axis would now produce the opposite direction of anisotropy.

In a paper that appears in the same issue of *Nature* as that by Steinle-Neumann and collaborators, Bruce Buffett (University of British Columbia) and Hans-Rudolf Wenk (University of California, Berkeley) take advantage of the new insights to calculate a possible orientation of crystals by magnetic fields. Their calculations produce a pattern of alignment consistent with the seismic data.[5]

Most experts believe that the inner core is composed of iron crystals in a hexagonal close-packed (hcp) structure (a few percent of the core comprises, possibly, nickel and some lighter elements). In the hcp structure, iron atoms in each plane sit on the corners of a hexagon, with one iron atom in the center. Such planes are then stacked, but offset against one another so that the atoms in one layer fit into the holes in the layer below. The crystallographic a-axis lies in these basal planes, and the c-axis is normal to them.

That's the structure that was assumed for the recent calculations of the elastic properties. Back in 1995, Stixrude and Cohen had done another calculation of the high-pressure properties of iron[4] but, faced with the great difficulty of incorporating the thermal effects, had opted to ignore them and run the model at 0 K.

To extend the calculations to high temperatures, Steinle-Neumann and his colleagues combined two techniques. First, they found the electronic wave function and the total energy by assuming a static lattice, with no motion of the nuclei. For this part, they used the very reliable density functional theory, which is based on a solution of Schrödinger's equation. Next, the theorists simulated the effects of temperature, with its random motion of the atoms, by a particle-in-a-cell method, in which one atom moves around in the mean-field potential of the other atoms, which are assumed to be fixed in position.

Steinle-Neumann and coworkers determined the ratio c/a of the length of the unit cell along the c-axis to that along the a-axis by finding the value that would minimize the free energy. They found that c/a grows with temperature, from about 1.6 near 0 K to about 1.7 at 6000 K. The lower value is consistent with that found in room-temperature experiments,[6] but such a strong increase with temperature was unexpected and still needs to be confirmed.

The increase in c/a means that the crystal is expanding with temperature and becoming softer in the c direction, leading to lower compressional velocities along that axis. Thus, as seen in the figure on page 17, at 6000 K the compressional wave goes slower parallel to the c-axis than at right angles to it, whereas the opposite is true at 0 K. A shear wave polarized in the c direction also shows a reversal of anisotropy with increased temperature.

Even though iron in the inner core is in the solid state, it can deform and slowly flow when subjected to stress. Experiments have indicated that hexagonal close-packed iron crystals tend to deform most easily through slippage along the basal planes, that is, the planes perpendicular to the c-axis. One can liken the iron crystals to playing cards, suggests Stixrude. When one stands a card deck on end and applies a shear force along the top, at right angles to the plane of the cards, the cards will tend to slip along one another until the deck lies flat on the table, with the cards now lying in the direction of the applied shear. In much the same way, the basal planes of iron crystals will orient parallel to flow lines.

Lining up the crystals

Soon after the discovery of the seismic anisotropy in 1986, Jeanloz and Wenk proposed that a convective instability, driven by a cooling in the inner core, might preferentially orient the crystals,[7] that is, give them "texture." Another process that might align the crystals is the asymmetric growth of the inner core; accretion of iron from the outer core gives it an equatorial bulge. Gravitational forces acting to rein in the bulge then cause a convective flow that pushes in at the midsection and out at the poles.[8]

In their recent work, Buffett and Wenk,[5] like Shun-Ichiro Karato of Yale University before them,[9] examined the pattern of orientation that might be caused by the magnetic field associated with Earth's dynamo. In general, magnetic field lines are expected to wrap in a corkscrew pattern around Earth's inner core with the axis of the corkscrew in the polar direction. Such field lines produce two types of forces on the crystals: Karato had considered the radially directed forces, and Buffett and Wenk focused on the azimuthally directed shear forces. Buffett said he and Wenk chose to study only the shear forces, even though the radial forces are probably stronger, because they believe that the stratification of the inner core will greatly inhibit any radial flow.

The shear forces are exerted over the surface of a sphere, much like hands rubbing along the outside of a ball. For an iron crystal on the equator of the inner core, such stresses cause the basal planes to be tangent to the equator, with the c-axis in the radial direction. A similar alignment occurs for crystals at other points in the core, in Buffett and Wenk's model. The result is thus consistent with the observed seismic anisotropy, with sound waves traveling slower in a direction parallel to the equatorial plane.

Buffett and Wenk's model is quantitatively detailed, starting with an aggregate of 500 crystal grains in random crystallographic orientations and looking at how they move in reaction to incremental changes in strain. The modelers have found that the crystalline alignment is greater when they include the effects of recrystallization, with each grain growing in size.

Not the last word

The new work signifies progress in solving the riddle of different acoustic travel times, but is not necessarily the final word on the subject. The theoretical calculations of single-crystal anisotropy would be strengthened by experimental verification. Experimenters have just recently developed the methods to study iron's elasticity at core pressures,[6] squeezing polycrystalline samples of iron in the jaws of a diamond anvil to measure the anisotropy of elastic properties at high pressures. So far the experiments haven't been extended to the very high temperatures of Earth's core, but experimenters are trying. They have also developed special techniques to separate out the single-crystal elasticity from the effects of texturing in their polycrystalline samples.[10]

The models of how single crystals become aligned in the inner core are more uncertain than the calculations of single-crystal properties because they must rely on assumptions about inner-core processes that are poorly known. The alignment may not result from a single force, such as that due to the electromagnetic stresses, but a combination of forces present in the inner core.

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