The Globe inside Our Planet

Earth's inner core is turning out to be an alien world

By RICHARD MONASTERSKY

In Dante's *Inferno*, the outcast Florentine poet took literary revenge on his political enemies by sentencing them to an eternity of torture without parole. They served their time locked inside Earth, writhing away in a circular, split-level hell, where the suffering grew more intense with each successively deeper and smaller layer.

Although modern geologists might scoff at Dante's portrayal of the world underground, the 14th-century writer was actually correct about the basic architecture of the planet. As geophysicists know today, the globe's interior consists of several spherical shells—an outer crust, a rocky mantle, and a metallic core—with the heat and pressure growing progressively more excruciating as the depth increases.

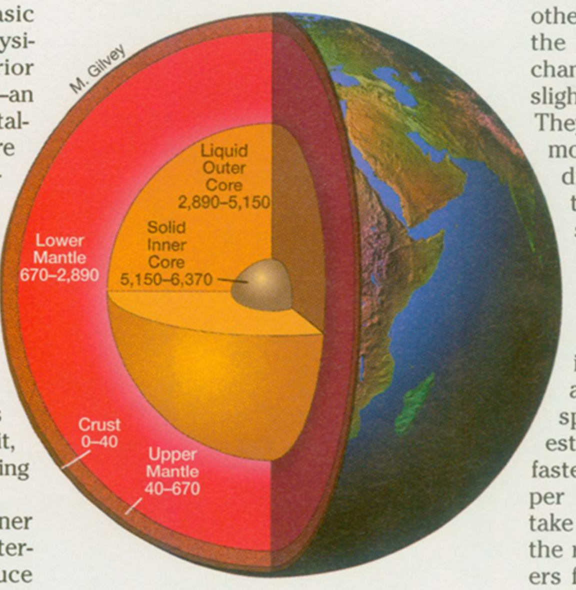
At the very center lies a solid sphere of iron as hot as the surface of the sun. Roughly the size of the moon, this so-called inner core remained for decades a terra incognita, hidden beneath 5,000 kilometers of solid rock and molten metal (see sidebar). Scientists knew so little about this distant orb that they tended to ignore it, preferring to spend their time exploring the regions closer to the surface.

"Up until just quite recently, the inner core has been thought to be an uninteresting, featureless place," says Bruce Buffett, a geophysicist at the University of British Columbia in Vancouver.

It turns out that researchers could have used a bit of Dante's imagination. Recent studies depict the inner core as a bizarre world locked inside our planet, where scientist's expectations often prove wrong. "It's become clear that the inner core is a lot more complex than we've given it credit for," says seismologist Kenneth C. Creager of the University of Washington in Seattle.

Two years ago, a pair of seismologists discovered evidence that the inner core is dancing to its own beat, spinning measurably faster than the rest of the planet. Now, researchers have found that the inner core appears to have a split personality, with one hemisphere manifestly different from the other. Both findings have flummoxed theorists who are trying to explain how such a strange body came to reside inside Earth.

"It's very puzzling," says Xiaodong Song, one of the researchers who gathered to discuss the inner core at a Boston meeting of the American Geophysical Union (AGU) in May. "As we learn more about the inner core, it shows more mystery. It's very difficult to explain." Song is a seismologist at Columbia University's Lamont-Doherty Earth Observatory in Palisades, N.Y.



A wedge taken out of Earth would reveal its four major layers: The thin and brittle crust, the solid rocky mantle, the liquid iron outer core, and the solid iron inner core. (Depth shown in kilometers.)

Song and his colleague Paul G. Richards exposed some of the core's curiosities in 1996 with their study of seismic waves pulsing through the deepest section of the planet (SN: 7/20/96, p. 36). The waves came from earthquakes in the South Atlantic and passed through the inner core on their way to recording stations in central Alaska, taking about 20 minutes to make the journey.

The two researchers noticed something peculiar in recordings made over a 30-year period. The seismic waves took progressively less time to cross through Earth, even though they were traversing exactly the same distance. Vibrations leaving a particular spot in the South Atlantic arrived at the recording station about three-tenths of a second sooner in the 1990s than they had in the 1960s.

The difference, they surmised, comes from an odd characteristic of the way seismic waves pass through the center of the planet. Researchers in the late 1980s found that the inner core transmits seismic waves faster in some directions than others. Song and Richards realized that the orientation of these paths would change if the inner core were rotating slightly faster than the rest of the planet. They hypothesized that the inner core's motion has slowly shifted the fastest direction of seismic wave travel so that it now lines up more closely with seismic waves going from the South Atlantic to Alaska. As a result, these waves get to Alaska quicker.

Since then, two other studies have bolstered the concept of an independently rotating inner core, although researchers disagree on its speed. Song and Richards originally estimated that the inner core is rotating faster than the mantle and crust by 1.1° per year, so the central sphere would take a little more than 3 centuries to lap the rest of the planet. In 1996, researchers from Harvard and the University of California, Berkeley calculated that the rate could be as high as 3° per year, whereas last year Creager figured a value of only 0.2° to 0.3° per year.

The different estimates of rates and other unresolved issues cause some seismologists to question whether the inner core is truly setting its own pace. In the July 3 SCIENCE, Annie Souriau of the Observatoire Midi-Pyrénées CNRS in Toulouse, France, wrote a commentary titled "Is the Rotation Real?" Souriau argues that the evidence to date does not build a convincing case.

If the core's rotation is real, it places stress on geophysicists who wrestle with the subject of Earth's internal forces. They find the concept of core rotation hard to explain because the solid iron sphere should be locked in step with the rest of the planet by the almost indomitable force of gravity, says Buffett.

The gravitational link comes from slabs of cold rock that have sunk from Earth's surface deep into the mantle. Because these slabs are extra dense, they tug on the solid inner core and raise welts a hundred meters or so that stick up into the fluid outer core. The attraction between these bumps and the cold mantle slabs exerts a powerful enough force to prevent the inner core from turning with respect to the mantle, says Buffett.

For Song and other seismologists to be correct, the inner core must somehow slip from its gravitational shackles and rotate freely. Buffett suggests that the inner core could do so if it were far softer than previously presumed. "If the inner core was very deformable and very mushy, then you can explain the observations," he says.

In this case, the inner core's surface could reshape itself quickly. The bumps could migrate across the top of the inner core while staying positioned directly beneath the cold, dense patches in the mantle, Buffett told researchers at the recent meeting in Boston.

From the lowest estimates of the inner core's speed, Buffett calculates that the solid iron sphere would have to be far softer than rock but harder than the glacial ice that flows readily down mountain valleys. Faster spinning rates would require an even more malleable inner core that could keep remolding its surface at a geologically frenzied pace.

If Earth's heart is softer than previously thought, less solid still are theories about the history of Earth's solid iron center. Geophysicists have only vague guesses about when the core first started solidifying and how quickly it is growing today.

The core itself probably formed quite early, even before Earth reached its full size 4.5 billion years ago, says geophysicist Raymond Jeanloz of the University of California, Berkeley. Under a barrage of giant asteroids, the fetal planet would have heated up enough for most of its iron to melt and sink toward the center, forming a molten metallic sea. As the steel soup cooled, crystals of iron started dropping toward the center. The solid core was born.

Just when that happened remains "mostly speculation," says Jeanloz. The best guess comes from studies of Earth's magnetic field, which was born in the roiling currents of iron in the outer core (SN: 10/19/96, p. 250). Because most scientists think that a magnetic field with the current strength and configuration requires a solid iron core, the field offers a clue to the inner core's origin, says Jeanloz.

Geologists know that a strong geomagnetic field existed at least as far back as 2 billion to 2.5 billion years ago because it left a magnetic imprint in ancient rocks. This indicates the presence of an inner core by that time. For periods even more ancient, the rock record is sparse and harder to read.

One of the biggest questions nagging researchers today concerns the orientation of the iron crystals in the inner core. This issue surfaced a decade ago when seismologists found that earthquake waves traveling north–south cross the inner core faster than those going east–west—a property called "anisotropy." The explanation they offered was that iron crystals line up to form a distinct pattern or fabric, which quickens waves going with the weave.

Seismologists first assumed that the entire inner core had a uniform crystalline design. Japanese and U.S. scientists are now discovering, however, that the strong pattern appears in only half the inner core.

Satoru Tanaka and Hiroyuki Hamaguchi of Tohoku University in Sendai, Japan, first uncovered this rent in the core's fabric by studying two classes of seismic waves from earthquakes. One group dives through the mantle and outer core, ultimately passing through the inner core before heading back to the surface. The other group travels almost exactly the same path in the mantle but bends around in the outer core and never reaches the inner core. By comparing the travel times of the two types of waves, Tanaka and Hamaguchi isolated the effect of the inner core.

Tanaka and Hamaguchi noticed that seismic waves going under Asia and Australia took the same time to crisscross the globe, no matter if they were traveling east–west or north–south. But for waves crossing under the Americas, Europe, Africa, and the Eastern Pacific—a region that corresponds roughly with the West-

Solid core proof ends half-century search

Dutch seismologists have detected a type of vibration that has eluded researchers for more than 50 years, providing the first direct evidence that the inner core is a solid.

"Many seismologists over several generations have been looking for signals like this," says Xiaodong Song, a seismologist at the Lamont-Doherty Earth Observatory in Palisades, N.Y. "If the observations are confirmed, it will be really exciting."

Researchers first identified the inner core in 1936 and hypothesized in 1940 that it might be solid. In 1946, Keith Bullen of the University of Sydney in Australia provided indirect evidence of the inner core's solidity when he observed that seismic waves speed up abruptly while passing through this region.

Bullen had studied one type of vibration—called compressional or P waves—which travels through materials by jiggling molecules parallel to the direction of the wave. The other type of vibration, shear or S waves, shift molecules side to side and can travel through solids but not through liquids, such as the outer core.

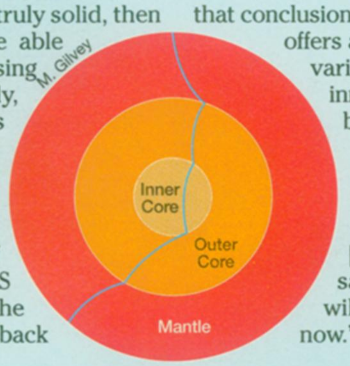
If the inner core were truly solid, then seismologists should be able to detect S waves passing through this central body, reasoned Bullen. By this thinking, P waves traveling through the outer core should convert part of their energy into S waves at the border of the inner core. The S waves would traverse the inner core, then convert back into P waves that would travel outward toward Earth's surface.

Bruce A. Bolt, a former graduate student of Bullen's, remembers searching with him through the monthly earthquake catalogues in the 1950s looking for evidence of these inner-core shear waves. "He never saw anything, nor did I," says Bolt, a professor emeritus at the University of California, Berkeley.

Now, Jeannot Trampert of Utrecht University in the Netherlands and his colleagues report that they have observed shear waves passing through the inner core. The researchers detected these subtle vibrations coming from two of the largest deep earthquakes this century, which occurred in 1994 below Bolivia and Fiji. By stacking together seismic recordings from many different observing stations, the Dutch researchers intensified the signal of the elusive waves. Trampert described their work in May at the Boston meeting of the American Geophysical Union.

Seismologists have not doubted that the inner core is solid because several lines of indirect evidence point toward that conclusion. The new work, however, offers a way to measure directly various properties of the inner core that could only be estimated in the past.

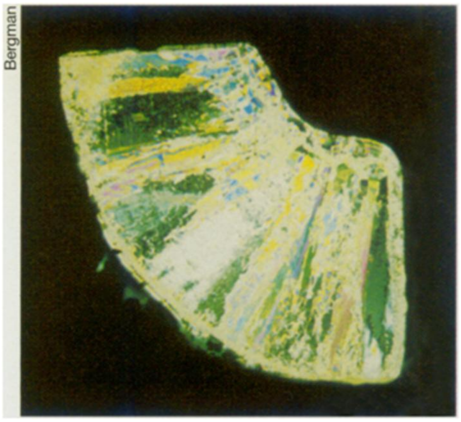
"Bullen once said to his colleague that he would die happy if he could observe evidence of [inner-core shear waves]," says Song. "So, I guess he will rest pretty peacefully now." *—R. Monastersky*



Catch a wave: Researchers have long pursued a set of seismic vibrations (shown in blue). It passes through Earth's inner core as a shear wave, which shuffles molecules side-to-side. One team has now captured examples of these waves.

ern Hemisphere—the north–south path took less time than the east–west path. The difference was roughly 3 seconds out of about 18 minutes. The scientists published their results in the February 10, 1997 JOURNAL OF GEOPHYSICAL RESEARCH.

Creager found similar differences in his study of core-crossing waves. The anisotropy in the Western Hemisphere is about 3 to 4 times the strength of the anisotropy in the Eastern Hemisphere, he reported at the AGU meeting this spring.



Bergman

Cold comparison: In a laboratory experiment designed to mimic the formation of the inner core, researchers use a rotating sphere of salt water that gets cooled from the center. Ice crystals grow outward from the middle in a pattern that may reflect the iron fabric of Earth's core. A vertical slice through the ice shows the crystal orientations.

The two-faced nature of the inner core has so far stumped researchers. "It's very surprising," says Creager. "It's hard to think of a physical mechanism that would cause these variations."

One answer might be that the temperature or chemistry of the eastern core differs from that of the western half. But when Creager averaged waves going in all directions across each hemisphere, he found no marked differences between the two sides of the core, indicating that they have the same general properties.

Instead, it appears that the pattern of the iron crystals in the Western Hemisphere lines up strongly in the direction of Earth's axis of rotation, whereas those in the Eastern Hemisphere show a more helter-skelter fabric, pointing in all different directions, with perhaps a slight bias toward the rotation axis, he says.

For now, geophysicists are still trying to answer the most basic question of why the iron crystals should align in the first place. Jeanloz proposed a decade ago that the solid iron of the inner core could actually be flowing slowly, carrying heat from its center toward its surface. The resulting currents would align the iron crystals as they flow—a process similar to what happens in glacial ice as it moves. If the convection is not uniform throughout the inner core, it could account for differences in the eastern and western halves, he says.

Others have questioned the idea of a churning inner core. "It's not clear why the inner core should be convecting. It's a metal and so is a good conductor of heat," says Michael I. Bergman, a physicist at Simon's Rock College in Great Barrington, Mass. If enough heat can escape from the inner core via conduction, then the solid iron would not need to flow.

In laboratory experiments, Bergman is testing an alternative hypothesis: The iron anisotropy develops because the crystals align themselves as they solidify from the molten alloy of the outer core. As liquid metal hardens, he says, it forms treelike crystals that grow outward into the remaining liquid. Theory suggests that the crystals should orient themselves parallel to Earth's equator because heat escapes fastest in that direction. Bergman is now testing that idea using a rotating sphere filled with salt water, cooled down to the point where ice crystals start to form, he reported at the AGU meeting.

By using an icy stand-in for the core, the physicist is unknowingly following *The Inferno.* Dante pictured the circles of hell leading down ultimately to a vast lake. In the middle of the basin sat Satan, beating his three wings so fiercely that they froze the water into a block of solid ice at the very center of the planet. Today's scientists don't expect to find anything so fanciful inside Earth, but they would agree that the inner core is turning out to be devilishly hard to fathom. □