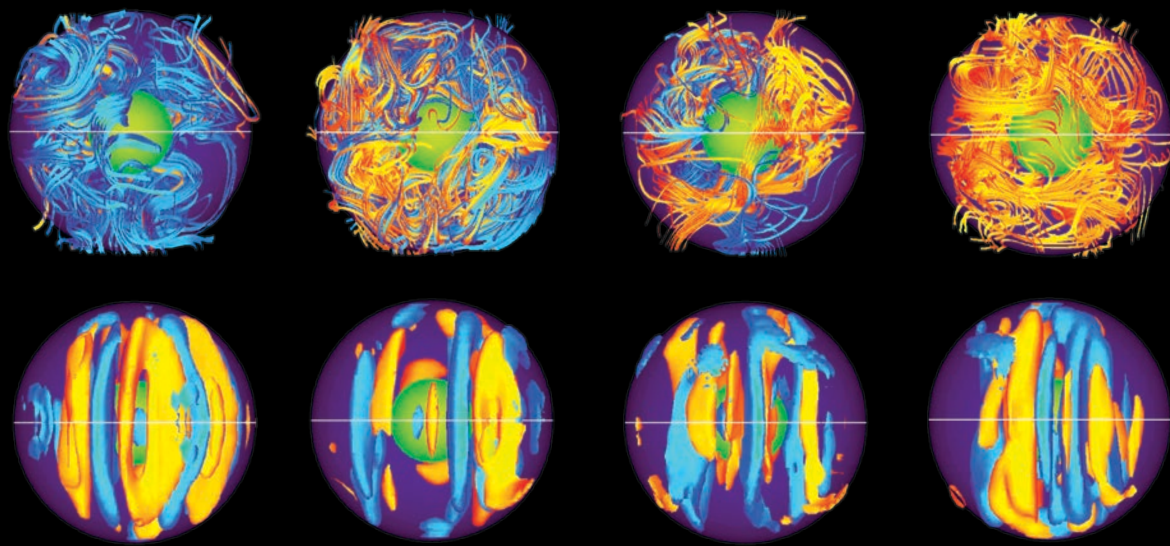


Mystery at the Center of the Earth

New research attempts to unravel the paradoxical past of the planet's magnetic field

By Thomas Sumner

Earth's depths are a hellish place. More than 5,000 kilometers belowground, the iron-rich core scorches at temperatures comparable to the sun's surface and crushes at pressures akin to the weight of 20 blue whales balanced on a postage stamp.

This extreme environment helps generate Earth's magnetic field, the planetwide force that makes life on the surface possible. When the sun occasionally belches a blast of electrically charged particles at Earth, the magnetic field redirects the incoming bombardment. Without this magnetic defense, solar storms would fry any unsuspecting life-forms on the surface and gradually strip away Earth's atmosphere (see Page 5).

For decades, scientists debated and fine-tuned their understanding of Earth's magnetism. Heat flowing through the liquid outer core helps slosh the molten iron, generating a magnetic field, the general consensus holds. In the last few years, however, new investigations of Earth's magnetic bodyguard have thrown a wrench into any sense of common ground. In 2012, scientists proposed that iron in the planet's core conducts heat more readily than previously thought. That would imply less mixing in the outer core and a young Earth with only a meager magnetic field, if any at all. Yet ancient rocks reveal magnetic records of an early, powerful magnetic field protecting the planet billions of years ago.

In January, supercomputer simulations offered a possible resolution to this paradox. Simulating how electrons ricochet around iron atoms at the extremes of temperature and pressure found in Earth's core suggested that iron's heat conductivity could actually be low enough to allow a strong magnetic field during Earth's youth. For a few brief weeks, researchers thought the mystery might be solved. In recent months, however, actual experiments using diamonds and lasers to re-create the intense conditions of the planet's core raise doubts

In a computer simulation, magnetic field lines (top row) twist and curl around the Earth's liquid outer core. This magnetism results from swirling, or convecting, liquid iron (bottom row). The simulation mimics the process of a polarity reversal in which Earth's north and south magnetic poles swap. Such reversals, a sign of a strong magnetic field generator, are seen going back hundreds of millions of years in planetary history.

P. OLSON/JOHNS HOPKINS UNIV.

that the paradox will be resolved so easily.

While the rising and falling conductivity predictions may seem like scientists running in circles, it suggests that a solution could be close, says Peter Driscoll, a geophysicist at the Carnegie Institution for Science in Washington, D.C.

"The community is never going to converge toward a solution until people start pushing from both directions," he says.

Freezing over hell

Earth's core is a giant heat-powered engine fueled mainly by energy left over from cosmic collisions, such as the one that formed the moon about 4.5 billion years ago. As the planet gradually cools off, this primordial heat flows through the liquid outer layers that surround the solid inner core. Some of the thermal energy transfers freely from atom to atom via conduction. The material remains stationary while the heat flows through it, like a cast iron skillet warming on a stovetop. When the heat flowing through a material exceeds what the material can handle through conduction, warmer patches can rise like the heated air in a hot air balloon, creating convection. In convection, the material itself moves.

This convection swirls the molten iron in the outer core. The sloshing liquid serves as a dynamo (*SN: 5/18/13, p. 26*). Within an existing magnetic field, a dynamo acts as an electrical generator to induce an electrical current in the flowing iron. This action produces its own magnetism, which strengthens and sustains the original field. If more heat flows by conduction rather than by iron-stirring convection, the dynamo weakens and the magnetic field wanes.

Five years ago, scientists thought that the iron in Earth's outer core transported a significant fraction of its heat through convection. In 2012, rather abruptly, everything changed. Several research groups independently proposed that more heat in the core moved via conduction, at a rate of about 150 to 250 watts per meter per kelvin. (The conductivity represents how many watts of thermal energy would pass through a 1-meter cube with a 1 kelvin temperature difference between two opposite sides.) That conductivity was about three times the value, 46 to 63 W/(m•K), scientists had previously used. With such a high conductivity, thermal convection in the core would be weak, if present at all. The magnetic field was in trouble.

"That's just an alarming statement to make," Driscoll says. "It's rare to see a jump effectively overnight by a factor of three." A robust magnetic field driven by thermal convection alone suddenly seemed unlikely.

Lucky for most forms of modern life, thermal convection isn't the only way to drive a dynamo. As Earth cooled, the iron in its core began to freeze from the inside out. The solid inner core currently grows by as much as 6,000 metric tons every second. Lighter elements such as oxygen and sulfur mixed in with the solidifying iron are expelled into the outer core. The buoyancy of the ousted elements helps churn the outer core and keep the dynamo running. So far, only about 4 percent of the core has frozen, leaving plenty of energy to keep the magnetic field going for potentially billions of years.

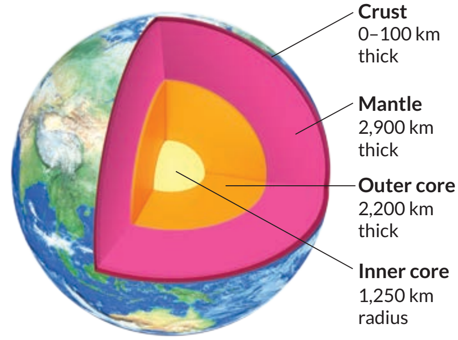
While the magnetic field's future is accounted for, its past still poses a problem. The 2012 conductivity estimates suggest that the inner core started freezing only within about the last 1 billion years. Before then, the sluggish thermal convection in the core could have generated only a weak magnetic field.

Yet the rock record shows otherwise. In July, geophysicist John Tarduno of the University of Rochester in New York and colleagues presented in *Science* the oldest record of Earth's magnetic field. By measuring magnetic impurities embedded inside ancient Australian crystals, the researchers demonstrated that a relatively powerful magnetic field varying between roughly 12 to 100 percent of its present-day strength enveloped Earth from about 4.2 billion to 3.3 billion years ago.

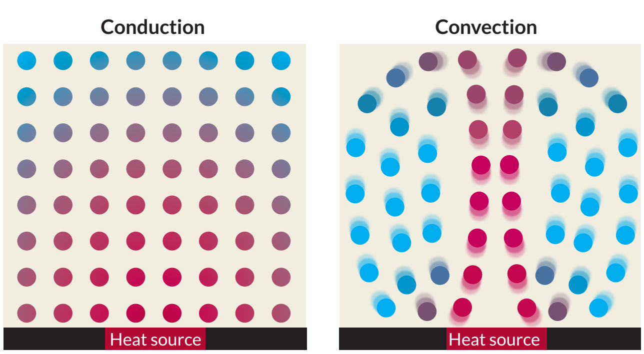
Earth's magnetic history since those early days is similarly confusing. Geophysicists expect that the field strength suddenly increased when lighter elements leaving the inner core began stirring the dynamo in a new way. "You have this new power source," says Peter Olson, a geophysicist at Johns Hopkins University. "You're plugging the dynamo into a 240-volt socket instead of a 120-volt socket — you should see that effect." But no such jump exists in the data, he says. In a 2013 paper in *Science*, Olson gave these dynamo dilemmas a name: the new core paradox. The mainstream theory and history of

Gooey center Below Earth's exterior lies the semimolten mantle, which makes up 84 percent of the planet's volume. Beneath the mantle is the iron-rich core. Once entirely liquid, the core is freezing from the inside out, creating a growing solid inner core.

SOURCE: USGS



Warm up Heat flows through Earth's liquid outer core by both conduction and convection. During conduction (left), heat (red) hops between stationary atoms. In convection (right), hot patches rise like molten globs in a lava lamp and cool patches (blue) fall. The movement churns iron in the liquid outer core and helps generate the planet's magnetic field.



FROM TOP: STOCKERNUMBER2/SHUTTERSTOCK, ADAPTED BY E. OTWELL; E. OTWELL

Earth's magnetic field just didn't match up, he wrote.

The 2012 papers that spawned the paradox were not the last word on the conductivity of Earth's core, however. Temperatures in the planet's heart can reach 6,000° Celsius and pressures can exceed 3 million times the atmospheric pressure at sea level. Without a real-life *Journey to the Center of the Earth*, there's no way to gather direct measurements. And scientists currently can't make accurate conductivity measurements for such extreme conditions in the lab. Instead, experiments typically take place at lower temperatures, below around 1,700°. The results from these more moderate conditions are then extrapolated to the conditions found in the core.

This extrapolation could introduce ambiguity because it assumes that iron doesn't significantly change its behavior between experimental and core conditions. But it just might. Earlier this year, researchers announced that the higher conductivity estimates may have overlooked something in the gap between relatively modest experimental conditions and the harsh environment in Earth's core — something that could possibly resolve the new core paradox.

Electron pinball

Understanding the conductivity of iron requires a deep knowledge of how electrons zip and whiz around iron atoms. In metals such as iron, free-moving electrons ferry electric charge and thermal energy. How readily iron conducts electricity and heat depends on how easily these electrons can travel.

At the temperatures and pressures found on Earth's surface, most of the resistance to the moving electrons is thought to come from the iron atoms themselves. Electrons collide with vibrating iron atoms, restricting the flow of electricity and heat. The iron in the core, however, acts very differently. Pressure in the core squeezes iron to more than 1.6 times its normal density, and the abundant heat gives electrons a speed boost.

Instead of trying to replicate core conditions in a lab, geophysicists Ronald Cohen and Peng Zhang of the Carnegie Institution for Science and colleagues created a detailed digital simulation of the iron in Earth's core. While previous versions used a simplified view of how electrons can interact, Cohen's team precisely tracked each individual electron's activities.

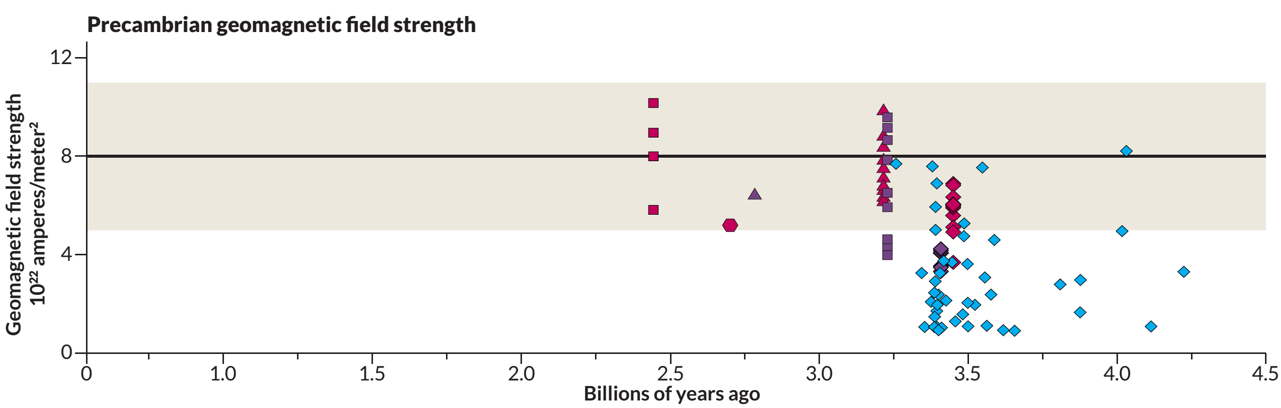
"We pulled out the big guns and accounted for every possible interaction," says Cohen. "We're doing the same type of calculation they do for predicting properties in high-energy physics at the Large Hadron Collider."

The team's simulation starts with a bundle of hundreds of iron atoms at the temperatures and pressures found in Earth's core. The computer program crunches all the quantum forces acting between each iron atom and electron before nudging every particle slightly forward in time. This process repeats over and over again until these snapshots create a video of how the electrons move around. The sheer number of simulated particles and the complex interactions between them are incredibly time consuming to calculate. Even with supercomputers, the simulation can't actually compute the exact conductivity. The researchers instead repeat the experiment again and again until the program can estimate the conductivity of iron with a low enough amount of uncertainty.

At the temperatures reached during earlier lab experiments, Cohen's simulation agreed with the previous higher predictions of iron's conductivity. Above around 1,700°, however, an overlooked interaction took center stage. In addition to electrons scattering off of vibrating iron atoms, the thermally energized electrons crossed paths more often and started colliding with each other. At core conditions, this electron-electron scattering became just as important as the electron-iron scattering. This addition essentially doubled the resistivity, which cut the thermal conductivity to about 105 W/(m•K), roughly half the 2012 estimates, the researchers reported in the January 29 *Nature*.

"Geophysicists can use our numbers and make the geophysics work," Cohen says. "They can explain the history of Earth's dynamo the way they want to and have been doing for some years."

The new conductivity estimate can indeed make the dynamo work, Olson and colleagues reported in the June issue of



Powerful protector In July, an analysis of ancient rocks suggested that a strong magnetic field has protected Earth for at least 4.2 billion years. The new magnetic measurements (blue diamonds) join a number of other studies that demonstrate that the planet's magnetic field has remained consistently strong throughout Earth's history. Tan shading represents the range of the modern magnetic field strength.

SOURCE: J. TARDUNO/UNIV. OF ROCHESTER

E. OTWELL

Physics of the Earth and Planetary Interiors. Plugging the new number into a simulation of heat flow through Earth's interior resulted in a convection-driven dynamo before the inner core formed. In this scenario, the magnetic field would still strengthen alongside the formation of the inner core. This magnetic boost, however, would be smaller, thanks to the boost in thermal convection, and could blend in with the natural variations in the magnetic field strength, says Aleksey Smirnov, a geophysicist at Michigan Technological University in Houghton.

Many geophysicists were cautiously optimistic that the new, lower thermal conductivity value could help undo some of the thorny problems that had arisen in recent years. The new conductivity was still only theoretical, however. It needs experimental results to confirm the presence of electron-electron scattering at higher temperatures. But so far, that's been hard to do.

Physicists reproduce the extreme conditions of Earth's interior by squeezing iron samples between two gem-quality diamonds.

K. HIROSE/TOKYO INSTIT. OF TECHNOLOGY

Under pressure

Re-creating the intense conditions of Earth's core requires finesse and a bit of bling. In his lab at the Tokyo Institute of Technology, high-pressure mineral physicist Kei Hirose and colleagues put the squeeze on disks of pure iron using a diamond vise. The iron samples are tiny — only around 20 micrometers in diameter and 10 micrometers thick, about a tenth the thickness of a sheet of copier paper. These small dimensions help the researchers evenly compress and heat the samples to something akin to the extreme conditions in the center of the Earth.

The iron goes between the tips of two 0.2-carat diamonds, which are unlikely to crack or warp under the extreme forces required during the experiments. Hirose likens the shape of the diamonds to Mount Fuji, each roughly cone-shaped with a tiny flat peak where the sample sits. The researchers gradually squeeze the two diamonds together for around 30 minutes until the iron is under corelike pressures. A carefully aimed infrared laser then heats up the sample to several thousand degrees. At last the sample is ready for examination.

Because the electrons in iron move both electric charge and heat, Hirose and colleagues can measure the electric conductivity and from that, infer the thermal conductivity. The researchers attach electrodes, typically made of gold or platinum, to the iron and run a current through the sample. The drop in the voltage across the sample lets the researchers know how strongly the iron resists the flow of electrons.

Recently Hirose's team conducted experiments above the approximately 1,700° threshold at which Cohen's group predicted electron collisions would become important. The experiments showed no evidence of electron-electron scattering, Hirose says. In fact, the experiments threaten to make the paradox even worse. The work suggested iron could be even more conductive as temperature climbs, and therefore less likely to convect, than previously thought.

In 2013, Hirose and colleagues predicted such a trend in *Physics of the Earth and Planetary Interiors*, suggesting that iron eventually reaches a point where the average distance an electron travels before bumping into an atom is comparable to the distance between each iron atom. At this point, with fewer remaining obstacles to bump into, the resistance to the movement of electrons will plateau even as temperatures continue to rise, they argue.

"Well, then we're back to the paradox for now, it seems," Smirnov said after hearing about the Hirose group's new findings.

Even with such high thermal conductivity values, the new core paradox may still be solvable, Driscoll said in May at a meeting of the American Geophysical Union and other organizations. A large enough heat flow through Earth's interior can generate convection even when conductivity is high, he says.

Extra heat could come from the decay of radioactive elements, he proposes. In April, researchers reported in *Nature* that the core could contain a significant amount of radioactive uranium and thorium. Driscoll calculates that even a relatively small amount of radioactivity in the modern core would translate into a sizable boost to the ancient magnetic field. If just a small amount of radioactivity warms the core today, that would mean that billions of years ago plenty of radioactive atoms would have been around to help fuel the heat flow, he explains.

"There are other knobs you can turn to get yourself out of the problem," Driscoll says.

Cohen, for his part, remains confident that electron-electron scattering causes lower core conductivity. "We've gone back and rechecked the robustness of our results, and it seems very strong," he says. He points out that experiments replicating the conditions in Earth's core can be finicky. It's possible Hirose and colleagues actually reached a lower temperature than they reported. Upcoming experiments by other research groups could still swing the pendulum one way or the other, he says.

For now, the riddle surrounding Earth's core and magnetic field will remain, as scientists debate what exactly is going on thousands of kilometers beneath the planet's surface. "I'm sure there's going to be a lot of back and forth over the next few years," Olson says. "But this is a good problem to have. This is the type of thing that gets people off their butts and motivates them to do more work." ■

Explore more

- Peter Olson. "The geodynamo's unique longevity." *Physics Today*. November 2013.