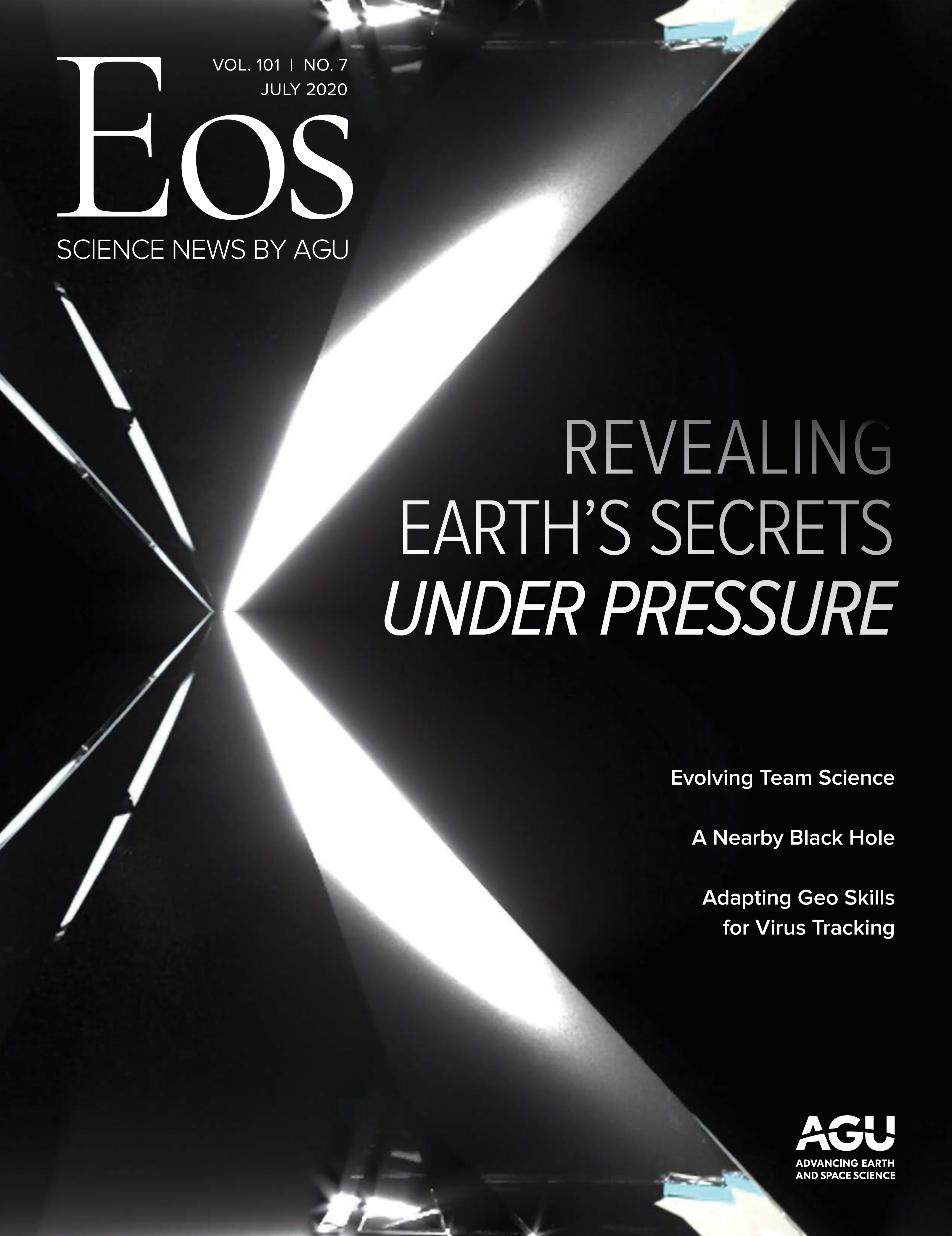

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Earth's Core Is in the Hot Seat

How old is Earth's inner core? High-pressure and high-temperature experiments suggest that our planet's inner furnace may be much younger than expected.

BY JENESSA DUNCOMBE


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Emerging research from high-pressure and high-temperature experiments suggests that Earth's inner core could be a "planetary babe" just under a billion years old—younger than Earth's oceans, atmosphere, and inhabitants.

These findings represent a drastic turn from how scientists thought Earth's inner core progressed from its molten beginnings to today—and a source of a contentious debate among geoscientists.

The uncertainty lies in conflicting measurements of the fundamental properties of metal. It's unclear how efficiently iron and iron alloys conduct heat within the core, making it difficult for researchers to describe how the core has cooled over time. Mineral physicists, geophysicists, condensed-matter physicists, and dynamicists are all trying to pin down an answer.

"It's a very provocative time at the moment, I would say, in terms of core studies," said Quentin Williams, an Earth and planetary sciences professor at the University of California, Santa Cruz.

In the past decade, scientists have invented novel ways to squeeze metal samples to extreme pressures while shooting lasers to heat the samples to temperatures as hot as the Sun's surface. The experiments are tricky, however, and a consensus is elusive. In the same issue of the journal *Nature,* June 2016, two research teams published the results of separate high-pressure, high-temperature experiments—with drastically different results.

"It's a very important topic because it's basically the boundary condition for the thermal history of the Earth," said Ronald Cohen, a researcher at the Carnegie Institution for Science in Washington, D.C. The answer could rewrite our understanding of Earth's history, paving the way for discoveries in Earth's dynamics at the surface, such as volcanism and plate tectonics, and helping to elucidate faraway worlds.

Research going back to the 1950s found fingerprints of the geodynamo in Earth's oldest surviving rocks.

Earth's Electrical Generator

"I think everybody agrees that both the mantle and the core are cooling," said Peter Olson, an adjunct professor of Earth and planetary sciences at the University of New Mexico. "What we'd like to know better is how fast."

Earth's core is made largely of iron, and it's split into two parts: a small, crystallized ball of hardened iron at the center of the Earth, called the inner core, and a liquid outer core that surrounds the inner core with a "roiling mass of molten metal," said Williams. Scientists have hypothesized about inner and outer iron cores since the 19th century on the basis of the composition of meteorites.

We can thank the core for the flourishing life on Earth. Convection in the outer core sustains the magnetic field that protects us from harsh solar radiation and keeps our atmosphere intact. As liquid iron flows through a weak magnetic field, it creates an electrical current inside the planet. In turn, this current induces a secondary magnetic field, which further induces a current inside the core. This loop creates a planetary-sized electrical generator at the heart of our planet called the geodynamo.

Researchers had assumed that the inner core must be very old because research going back decades found fingerprints of the geodynamo in Earth's oldest surviving rocks, dating back nearly 4 billion years.

And indeed, the idea of an old inner core "sounded reasonable," said Kei Hirose, a professor of geophysics at the University of Tokyo and director of the Earth-Life Science Institute at the Tokyo Institute of Technology. It checked the important box: An old inner core fueled the geodynamo for billions of years by driving thermal convection in the outer core.

Metallurgy Lends a Hand

But Hirose noticed that few people had measured the thermal conductivity of iron under extreme conditions, and the few studies that had been completed, using shock wave experiments, had large uncertainties and were not easily reproducible. The thermal conductivity could be a crucial value to pinning down the core's dynamics: The core cools via both convection and conduction, and how fast it conducts heat controls how much heat is left over to drive convection.

The scientific literature listed values for the conductivity, but the values were "highly speculative," said Hirose. So instead, the team turned to research from a different field from a science based on ancient civilizations: metallurgy. Metallurgy is the study of metals, and its beginnings go back to early human settlements when forging metals was the ticket to fortifying armies. Metallurgy lives on today as a branch of materials science tasked with mineral and metal processing.

"Such literature was not known in the geoscience community," Hirose said. Combing through metallurgy papers and conducting high-temperature experiments in the lab, Hirose's team concluded that the assumed relationships between electrical resistivity and iron broke down at high temperatures, suggesting that the thermal conductivity of iron was actually quite high. If their findings were correct, the core was cooling very, very quickly.

The finding "broke all the models," said John Hernlund, a professor and vice director of the Earth-Life Science Institute. Hernlund, Hirose, and others wrote up the findings in a bombshell paper in 2013 that "created a virtual earthquake in the geophysics community," said Hernlund.

In a perspective published in the journal *Science* later that year, Olson named the issue the "new core paradox." If the core is cooling much faster than we thought, "the best way around this paradox is to think beyond the standard model of core evolution," Olson wrote. If the inner core was, in fact, very young, researchers needed to better explain how the geodynamo is driven.

Diamond-Clad Lab Work

The *Science* paper sparked a flurry of new experiments and investigation into theory.

The two papers released in the same issue of *Nature* in 2016 showed experimental takes on pinning down the core's thermal behavior.

The authors of both papers used diamond anvil cells, a high-pressure lab device. The cells contain two diamonds, polished perfectly into cones with their tips shaved off. The scientists place a thin slice of iron—no thicker than a human hair—between the diamonds' tips.

For decades, scientists have taken advantage of Earth's hardest mineral, diamond, for lab experiments. No other mineral can scratch it, and when two opposing diamonds are perfectly aligned, they can pinch a slice of iron to pressures far greater than those of Earth's core.

Hirose, who frequently used diamond anvil cells in the lab, said that even though the diamonds are strong, the slightest variation in shape can cause them to crack under high pressures. Expert polishers smooth the sides of the diamonds to within 1 micrometer, the width of a small bacterium. Hirose called one particularly skilled technician "our treasure," because few can achieve such precision.

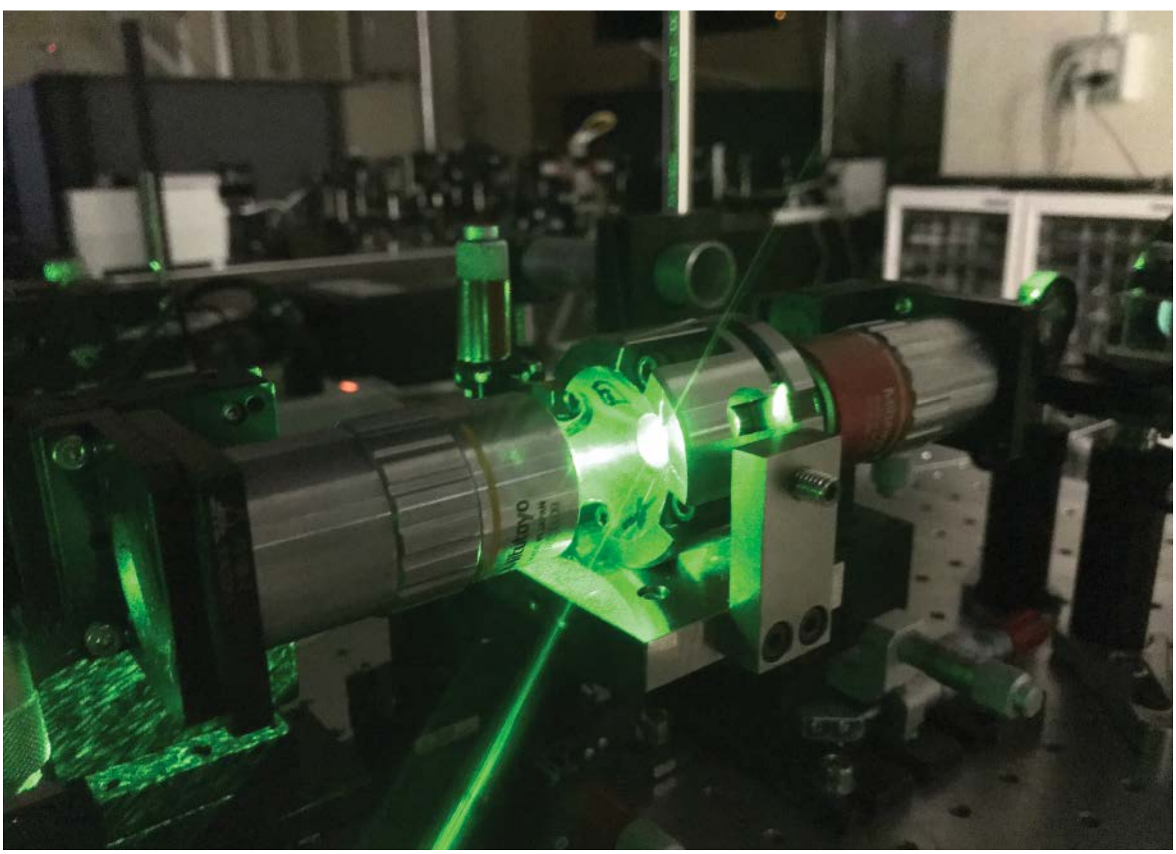
Diamonds have another plus as well: Researchers can shoot lasers through their translucent sides to send a pulse of heat into the sample. Both studies used lasers to heat their samples to thousands of kelvins.

A Tale of Two Papers

In one of the diamond anvil experiments, a team in Washington, D.C., measured the thermal conductivity of iron using two lasers to quickly heat the sample and measure its inferred temperature change.

In the other experiment, a different research team based in Tokyo measured iron's electrical conductivity, a property closely related to thermal conductivity, and then used an empirical relationship to calculate thermal conductivity.

The papers found contradictory results, and their discrepancies reveal just how difficult high-pressure experiments can be. The Tokyo group proposed a thermal conductivity value of 88 (+29/−13) watts per meter kelvin at the core-mantle boundary, whereas, the Washington, D.C., group proposed 25 (±7) watts per meter kelvin. The disparity in values may seem small but could mean the difference between an inner core that is billions of years old and a relative newcomer to Earth's internal structure.



In a thermal conductivity experiment, researchers shoot a green laser through a diamond anvil cell to heat an iron alloy sample. Credit: Kenji Ohta

The experimental differences "may have to do with the preferred crystal orientation in the samples," said Stewart McWilliams, a researcher at the University of Edinburgh and a coauthor of the study by the Washington, D.C.–based team.

Hirose, who led the team in Japan, agreed that the pressure used to compress the samples would affect the orientation of the crystal grains in iron, and the two teams had indeed taken measurements perpendicular to each other.

Stewart said he and others are now focusing on modeling the systematic errors in the experiments that could bias measurements. These errors "go a little way" in explaining the discrepancies, "but not enough," he said.

Time will tell whether a middle ground is the answer. Quentin Williams, who was not involved in either study and published a review of thermal conductivity research in the journal *Annual Reviews of Earth and Planetary Sciences,* wrote that "nevertheless, while recognizing that intermediate assertions are highly hazardous…it would not be surprising (to this author) if thermal conductivity values, with improved theoretical and experimental refinements, ultimately converged to values within a broad range of 35 to 80 watts per meter kelvin at the conditions of the top of the outer core."

Diamonds are one of the hardest materials on Earth, and scientists can use them to compress iron to pressures inside Earth's core. Credit: Kei Hirose

A Compositional Compromise

When Earth coalesced from a homogenous rubble pile into its differentiated, layered state, its material separated by density. Buoyant material like water, air, and silicates stayed on top and in the middle, and dense material like iron sank to the center.

Discerning the thermal evolution of Earth "will pose a challenge for the next 15 years for the community."

But according to seismic research that goes back to the mid-20th century, Earth's core isn't pure iron. Seismic measurements show that it's about 10% less dense than pure iron and is composed of alloys likely including nickel and some special recipe of lighter elements, perhaps silicon, oxygen, magnesium, and carbon.

This could be good news for the core paradox, however. The presence of lighter elements may propel convection in the core, giving the geodynamo a source of convection even if thermal convection is too weak. If lighter elements cause convection, this source of buoyancy gives a work-around to the core paradox.

Cohen, Hirose, and many others are investigating the effect of lighter elements on heat transport in the core. "It is a totally, totally open question," Hirose said.

Novel follow-up studies are upping the ante as well. Kenji Ohta, an associate professor in Earth and planetary sciences at Tokyo Institute of Technology, said that his lab is exploring a way to melt samples at high temperatures and pressures, something that brings scientists one step closer to mimicking Earth's liquid outer core. Past studies have been conducted, for the most part, on solid samples.

"This is exciting stuff," Williams said of the race to find an answer. The question of the core and thermal evolution of Earth "will pose a challenge for the next 15 years for the community."

"It's the pivotal issue in Earth's evolution and the evolution of our magnetic field," Williams added. "It's something that ultimately just has to be figured out. And so, when challenges like this are posed to the community, sometimes they are answered slowly because getting a good answer is difficult. But ultimately, they will be answered. I'm really optimistic about it."

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