GEOPHYSICS

Earth's core problem

Measurements of the electrical resistance and thermal conductivity of iron at extreme pressures and temperatures cast fresh light on controversial numerical simulations of the properties of Earth's outer core. SEE LETTERS P.95 & 99

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Earth's core acts like a storage heater, with heat released during crystallization of the inner core that buffers the slow cooling of the planet as it radiates its heat to space. The most obvious expression of this heat transfer is Earth's magnetic field, which is generated by convection in the liquid outer core. But the magnitude of the transfer is controlled by thermal conduction across the boundary between the core and mantle.

In 2012, first-principles numerical simulations[1,2] indicated that the thermal conductivity of liquid iron in the outer core is so high that this region might act as a pump that pushes heat towards the core–mantle boundary faster than convection can. If, as these controversial studies suggest, the core is losing heat at such a high rate, it means that the magnetic field must work in previously unimagined ways[3], and that the solid inner core must be less than a billion years old[4] — a mere babe in planetary terms. In this issue, Ohta *et al.*[5] (page 95) and Konôpková *et al.*[6] (page 99) report studies that experimentally tested the simulations' results using complementary, but distinct, approaches and come to different conclusions.

Both groups use laser-heated diamond-anvil cells to generate the extreme temperatures and pressures of the core–mantle boundary, but that is where the similarity ends. Ohta *et al.* measured the electrical resistance of iron wires, which is closely related to the wires' thermal conductivity (Fig. 1a). To convert the resistivity measurements to a measure of the thermal conductivity of liquid iron in the outer core, the authors fitted their data to a model of resistivity that assumes that resistance approaches a limit at high temperature (a phenomenon called resistivity saturation). This then allowed them to use the Wiedemann–Franz relationship between resistance and thermal conduction in metals to calculate the thermal conductivity. Both of these procedures have good theoretical bases and are well established for low-pressure observations. The observed high electrical conductivities resulted in a predicted outer-core thermal conductivity of around 90 watts per metre per kelvin, which is in reasonable agreement with the 2012 simulations[1,2].

By contrast, Konôpková *et al.* directly measured thermal conduction by watching a heat pulse propagate through a solid iron sample after heating with a nanosecond laser pulse (Fig. 1b). The time taken for the pulse to pass from the heated side of the sample to the other side, and the amplitude difference of the pulse between the two sides, are functions of the thermal conductivity of the sample, as well as of the surrounding solid medium that transmits pressure from the diamonds to the sample and thermally insulates the sample from the diamonds. After some careful mathematical modelling of the temperature field in the diamond cell, the authors extracted the thermal conductivity of iron from time-resolved changes in the brightness and wavelength of the glow from the white-hot sample. They obtained a thermal conductivity of about 30 $\mathrm{W\,m^{-1}\,K^{-1}}$, similar to early predictions of outer-core conductivity[7].

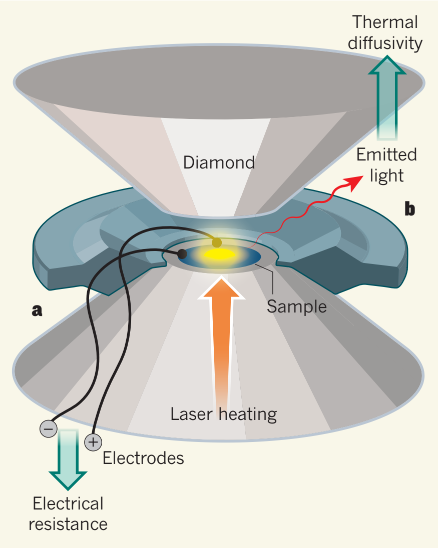

Figure 1 | Measuring the thermal conductivity of iron at Earth's core conditions. In diamond anvil cells, the pressure generated between the tips of diamonds can exceed millions of atmospheres. Lasers can be fired through the diamonds to directly heat a sample of a material to 4,000 kelvin or more. **a**, Ohta *et al.*[5] connected electrodes to a sample of solid iron and measured its electrical resistance (which is inversely proportional to thermal conductivity in metals) at high temperatures and pressures. **b**, In separate experiments, Konôpková *et al.*[6] pulsed the laser, and measured the time taken for heat pulses to diffuse through a solid iron sample on the basis of changes in the brightness and wavelength of the light emitted from the sample. This allowed them to measure the thermal rate of diffusion, which is closely related to thermal conductivity.

But this leaves us with a conundrum: how to reconcile the high thermal conductivity reported by Ohta and colleagues on the basis of resistance measurements with the low thermal conductivity measured by Konôpková and co-workers. Maybe there were unknown complications with the experiments? For example, the extremely short laser pulses used by Konôpková *et al.* might have caused the sample to partially melt for a short period, which could have gone unnoticed during the experiment. If so, then the melting phase transition would have acted as a thermal buffer (much as the crystallization of the inner core buffers Earth's temperature) and caused an apparent decrease in thermal conductivity. This might explain why the measured thermal conductivities decrease so strongly with temperature, particularly at temperatures approaching the melting temperature.

Or maybe Ohta *et al.* underestimated the heat loss through the electrodes in their experiments, which would mean that the average sample temperature was less than the measured value. This could have made it look as though resistivity was saturating, even if it wasn't. Alternatively, the proportionality constant between electrical resistance and thermal conduction (the Lorenz number) might become strongly temperature dependent at the extreme pressures and temperatures of the experiment — this would point to previously unobserved fundamental physics.

Despite the discrepancy, these two studies are experimental feats, measuring complex physical properties of samples smaller than a pinhead at pressures greater than 1 million atmospheres, and at temperatures above 4,000 K. The fact that the results agree within a factor of three is a remarkable success, but the devil is in the detail. The discrepancy makes a big difference to estimates of when the inner core formed, and hence when Earth generated a stable magnetic field — the inner core could be as little as 700 million years old, about the same age as complex life; or as much as 3 billion years old, about three-quarters of Earth's age. More experimental and theoretical work is needed to resolve the discrepancy and hence to constrain the age of the inner core and the workings of Earth's magnetic field. ■

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