Earthly powers

In 1862, British physicist Lord Kelvin (William Thomson) tried to estimate the Earth's age, working from a simple theory of the cooling process from primordial times. He assumed a constant, temperature-independent conductivity of the Earth's interior, and no internal sources of heat, arriving at an estimate of 98 million years. Thirty years later, another physicist, John Perry, pointed out that, should the Earth's thermal conductivity decrease with temperature, the estimated age might become much longer, even as long as billions of years. Perry was right.

The presence of radiogenic heating — internal heat created by the decay of long-lived radioactive isotopes — was unknown to Kelvin, and had little to do with his poor estimate. Yet Kelvin was poking around some deep mysteries. Radiogenic heating does play an important role in the Earth's interior geophysical dynamics, and might even be a major driver of all mantle convection — responsible for volcanoes and plate tectonics. The evidence is only slowly accruing, as it relies on detecting the most elusive particles currently known — neutrinos.

Geophysicists estimate that the total heat flow outward from the Earth's interior to its surface is around 47 TW. Some of this heat is primordial, a remnant of the hot early conditions during the Earth's formation. The rest is clearly radiogenic, and yet the relative contribution of the two remains highly uncertain. We have no way to know how much primordial heat remains, and have only elusive neutrinos streaming from radioactive decays to tell us about the radiogenic contribution. Various models, based on assumed chemical and physical properties within the Earth's interior, yield estimates in the range of 15–41 TW for the radiogenic component and 12–30 TW for remaining primordial heat.

For the radiogenic component, the principal unknowns are the total rates of decay of ^{232}Th and ^{238}U, which have been the focus of study by two international collaborations, KamLAND and Borexino. Both have been trying to detect antineutrinos from such decays — geoneutrinos — and the KamLAND team made the first detection of such neutrinos ten years ago. Last month, the Borexino group published its latest findings (*Phys. Rev. D* **92,** 031101(R); 2015), which point to higher radiogenic heating than previously expected — yet also underline just how slow and difficult this research is.

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Both groups use large underground liquid scintillation detectors, and have previously reported geoneutrino detections with very high confidence. Just confirming their presence isn't easy and took years of work, primarily because of the need to distinguish real geoneutrinos from those generated by nuclear reactors, and eliminating other potential sources of detector triggers. But the more important aim is to learn from these detected neutrinos more about the distribution of radioactive isotopes within the Earth's interior, and also about how much heat they deliver.

The Borexino detector operates at the underground Gran Sasso National Laboratory in Italy. Between December 2007 and March 2015, it recorded 77 candidate geoneutrino events, a substantial increase over the 46 detected events the team reported in 2013. Correcting for antineutrinos generated by nuclear reactors dotted around the globe, the team calculated that about 53 of the 77 detected antineutrinos were likely to be from reactors, leaving about 24 true geoneutrinos. That is, only three per year detected from the entire Earth. These can be assumed to represent decays of ^{238}U or ^{232}Th, as only these produce antineutrinos of sufficient energy to trigger the detectors. This data demonstrates the existence of geoneutrinos beyond any reasonable doubt.

A second question is where are these antineutrinos coming from — the relatively shallow Earth's crust, or deeper mantle? In 2013, the Borexino group, combining their data with that of KamLAND, found results suggestive of at least some neutrinos coming from the mantle (*Phys. Lett. B* **722,** 295–300; 2013). With the larger dataset, the team now asserts that the chance that their mantle signal is a false positive is less than 2%. More importantly, the data is now becoming strong enough to make crude estimates of how many of the geoneutrinos come from within the Earth's mantle, rather than the crust. It seems to be about half.

Going one step further, the researchers also estimated the total amount of heat generated by radiogenic heating, finding about 33 TW (with large error bars) — higher than earlier studies. This might actually be enough for radiogenic heating alone — even in the absence of significant primordial heat — to drive mantle convection.

However, these results aren't wholly independent of theory. They require an estimate of the number of neutrinos coming from the Earth's crust, and this is based on the measured abundance of uranium and thorium in crustal samples. Subtracting this signal leaves the mantle contribution. It also requires a model-dependent inference from the detected geoneutrino flux to the distribution of radioactive isotopes throughout the earth. One interesting aspect of this ongoing work — suggested to me by Jason Detwiler of the KamLAND group — is that there is a small disagreement persisting between the Borexino and KamLAND results for the number of mantle geoneutrinos.

So far, the KamLAND results are consistent with a slightly lower contribution from the mantle than the Borexino results. The disagreement has persisted as each group has updated their findings (KamLAND in 2013 and Borexino now). What will happen next? It might very well be that the distinct geology of the two sites — in Japan and Italy — may account for these differences, and they'll disappear as more becomes known about those differences. Or, more interestingly, the disagreement could grow, pointing to fundamental problems or errors in the models used to interpret the geoneutrino results.

Next up will come the SNO+ collaboration, operating a detector located some 2 km underground in Sudbury, Canada. This should help get even more accurate estimates of the true rate of radioactivity within the Earth. It's surprising in one sense that we still struggle to understand such basic questions — what are the sources of heat within our planet? Yet finding answers turns out to demand the most sensitive detectors we can muster, using the most advanced physics. ❐

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