

EARTH'S HEAT BUDGET

Clairvoyant geoneutrinos

The quantity of heat generated by radioactive decay in Earth's interior is controversial. Measurements of geoneutrinos emitted from the mantle during this decay indicate that this source contributes only about half of Earth's total outgoing heat flux.

Jun Korenaga

Four-and-a-half billion years ago, Earth formed as a hot mass of matter. Since then, the planet has been gradually cooling. In the process, it has been slowly releasing its primordial heat. But at the same time, heat is continually generated inside Earth, as radioactive isotopes in the mantle decay. Understanding Earth's thermal budget is key to unravelling its evolution, but this type of planetary bookkeeping is a difficult task. At present, Earth is releasing heat from its surface at a rate of about 46 terawatts¹. It has been the subject of much debate how much of this heat flux comes from residual primordial heat and how much comes from radioactive decay. Writing in *Nature Geoscience*, the KamLAND Collaboration² reports direct measurements of the flux of heat generated by radioactive decay in Earth's mantle and finds that radiogenic heating accounts for only about half of the total heat flux, so Earth is consuming its primordial heat to supplement the rest.

Planetary cooling is achieved mainly through the process of mantle convection. Convection helps transfer heat from the deep interior towards the surface. Therefore, the relative contributions of primordial versus radioactive heat to the total convective heat flux are key factors to understand planetary evolution. More than half a century ago, Harold Urey³ suggested that Earth's thermal budget might be completely balanced, so that at any point in time, as much heat is released at Earth's surface as is produced in its interior.

His idea was based on the notion that mantle convection is self-regulated; if more heat were produced than released, for example, the mantle would heat up and convect more vigorously to lose more heat and reach a thermal equilibrium. In this framework, loss of any primordial heat is entirely supported by the continued radiogenic production of heat; in other words, Earth does not cool down at all. However, geophysical theories⁴ developed in the early 1980s showed that this idea was self-contradictory and Earth should cool



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Figure 1 | The KamLAND detector facility, Japan. Through measurement of geoneutrinos, emitted during the radioactive decay of isotopes in Earth's mantle, the KamLAND Collaboration² demonstrates that radioactive decay contributes only around half of Earth's total outgoing heat flux. The remainder of the outgoing heat must be residual primordial heat left from the planet's formation.

down. But these studies also suggested that a dominant fraction (70–80%) of Earth's convective heat flux should still come from radiogenic heating.

Alternatively, the relative contributions of primordial heat and that from radioactive decay can be estimated using a geochemical approach. Heat generated within Earth comes mostly from the decay of just four isotopes, uranium-238, uranium-235, thorium-232 and potassium-40. So, if the composition of Earth was known in detail, this information alone would be sufficient to finalize the thermal budget. This geochemical approach would be most straightforward because the above geophysical approach depends on various assumptions on mantle dynamics. Estimating the composition of Earth's interior is, however, notoriously difficult

and the chemical structure of the mantle is widely debated^{5,6}.

From various rock samples collected on the surface, it is possible to estimate the composition of the mantle down to about 200 km. But Earth's mantle is about 3,000 km deep. Current compositional models⁷ assume that the mantle is reasonably well mixed by convection. By examining the compositional trend in those shallow mantle rocks and also by taking into account the elemental abundance in the Solar System, these models predict that only about 30% of the convective heat flux is sourced from radioactive decay. The mantle may, however, be layered⁸, and the shallow mantle may bear no resemblance to the deep mantle. This would make it impossible to estimate the amount of heat generated by radioactive decay based on the composition of the shallow mantle⁹.

Neutrino physics has the potential to resolve this frustrating situation. The process of radioactive decay emits antineutrinos — electrically neutral particles that can pass unaffected through virtually any matter. So, however deep the radioactive isotopes are buried in Earth, their decay can be measured directly by recording the emitted antineutrinos at the surface. Because these antineutrinos are emitted during radioactive decay within Earth, they are called geoneutrinos. The catch is, of course, that geoneutrinos are extremely difficult to detect because they pass through virtually everything. By using large-volume instruments that were originally built for particle physics, however, physicists have begun to measure geoneutrinos. First measurements¹⁰ were too uncertain to be geologically useful, but improvements in the technique now mean that the results can be used to assess the relative importance of radiogenic and primordial heat in Earth's heat flux.

The Kamioka Liquid-Scintillator Antineutrino Detector (KamLAND) Collaboration² reports measurements of geoneutrinos emitted between 2002 and 2009 near Kamioka, Japan. They combine their results with existing, though less precise, measurements taken from a similar detector in Gran Sasso, Italy¹¹. According to these data, the decay of uranium-238 and thorium-232 together contribute around 20 terawatts, a bit less than half, of Earth's

total outgoing heat flux. Geoneutrinos emitted during the decay of uranium-235 and potassium-40 are below the detection limits of the experiments, but they are not expected to contribute much because their relative abundances to uranium-238 are known to be very low at present. Overall the experiments indicate that radioactive decay within the mantle contributes between 16% and 68% of the total convective heat flux from Earth.

If no more than 68% of Earth's convective heat flux comes from radioactive decay, the planet's thermal budget cannot be balanced, ruling out the possibility of a perfect thermal equilibrium suggested by Urey³. Also, Earth's primordial heat supply could potentially contribute more to the convective heat flux than the 20–30% predicted by the non-equilibrium geophysical models of Earth⁴. In contrast, the measurements of radioactive heat production are compatible with estimates from those geochemical models that assume a well-mixed mantle.

One caveat is the limited geographical coverage of geoneutrino observations. With only one or two detectors, interpretations of the data have to assume that radioactive isotopes are evenly distributed in a spherically symmetric Earth. Until geoneutrino detection can provide a dense network of observations, it will be impossible to distinguish with final certainty between the currently debated models of Earth's mantle^{5,6}, most of which have complex three-dimensional

structures. Nonetheless, the progress made at KamLAND must be commended for its astounding rate of improvement.

The KamLAND Collaboration² demonstrates that the total flux of heat from Earth's surface comes from both the residual primordial heat generated when the planet formed and heat that is continually produced by radioactive decay. The results improve our understanding of Earth's planetary evolution by ruling out models of a thermally balanced planet. As our understanding of other terrestrial planets such as Mars and Venus depends largely on what we have learned from Earth, a more accurate understanding of Earth's thermal budget will be essential for a better theory of planetary evolution. □

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PLANETARY SCIENCE

Arrow in Titan's sky

An exotic arrow-shaped cloud was discovered in the atmosphere of Saturn's moon Titan last year. Numerical modelling shows how a large-scale atmospheric wave can naturally shape tropical clouds to such an arrow.

Tetsuya Tokano

The lower atmosphere of Saturn's moon Titan harbours spotty and streaky methane clouds. These clouds produce rainfall from time to time. Observations have so far focused on the location and timing of cloud occurrence, because both features are quite different from those of terrestrial clouds. Their shape or orientation, on the other hand, had received less attention — until a big, mysterious cloud in the form of an arrow appeared in the tropical sky of Titan¹. Writing in *Nature Geoscience*, Mitchell and colleagues² use a three-dimensional climate model to explain the dynamics of Titan's tropical weather.

Methane clouds can tell us much about the dynamics of Titan's troposphere — the lower portion of its atmosphere where, otherwise, wind data are sparse. For example, short-lived, spotty clouds are indicative of localized strong updrafts, termed convection³. And seasonal changes in global cloud coverage can constrain global patterns of atmospheric circulation^{1,4}. Tracking the apparent motion of clouds is a common method to estimate wind speed and direction^{1,5}. But clouds can also reveal atmospheric waves or tides that are superimposed on the mean atmospheric flow.

Waves do not directly transport the cloud particles themselves. Instead, they propagate the horizontal and vertical patterns of

local airflow over large distances. Thereby, waves modulate the cloud pattern through convergence and divergence of air along the line of wave propagation. These effects create the impression that the cloud itself is moving. The appearance of clouds on Titan, first in the tropics and then at high latitudes, was interpreted as evidence for southward-propagating large-scale waves⁶. Furthermore, a wavy pattern in the longitudinal distribution of clouds has been interpreted as a result of atmospheric tides caused by Saturn's gravity field⁴.

Mitchell and colleagues² scrutinized the shape of an eye-catching cloud near Titan's equator, with a view to exploring the moon's