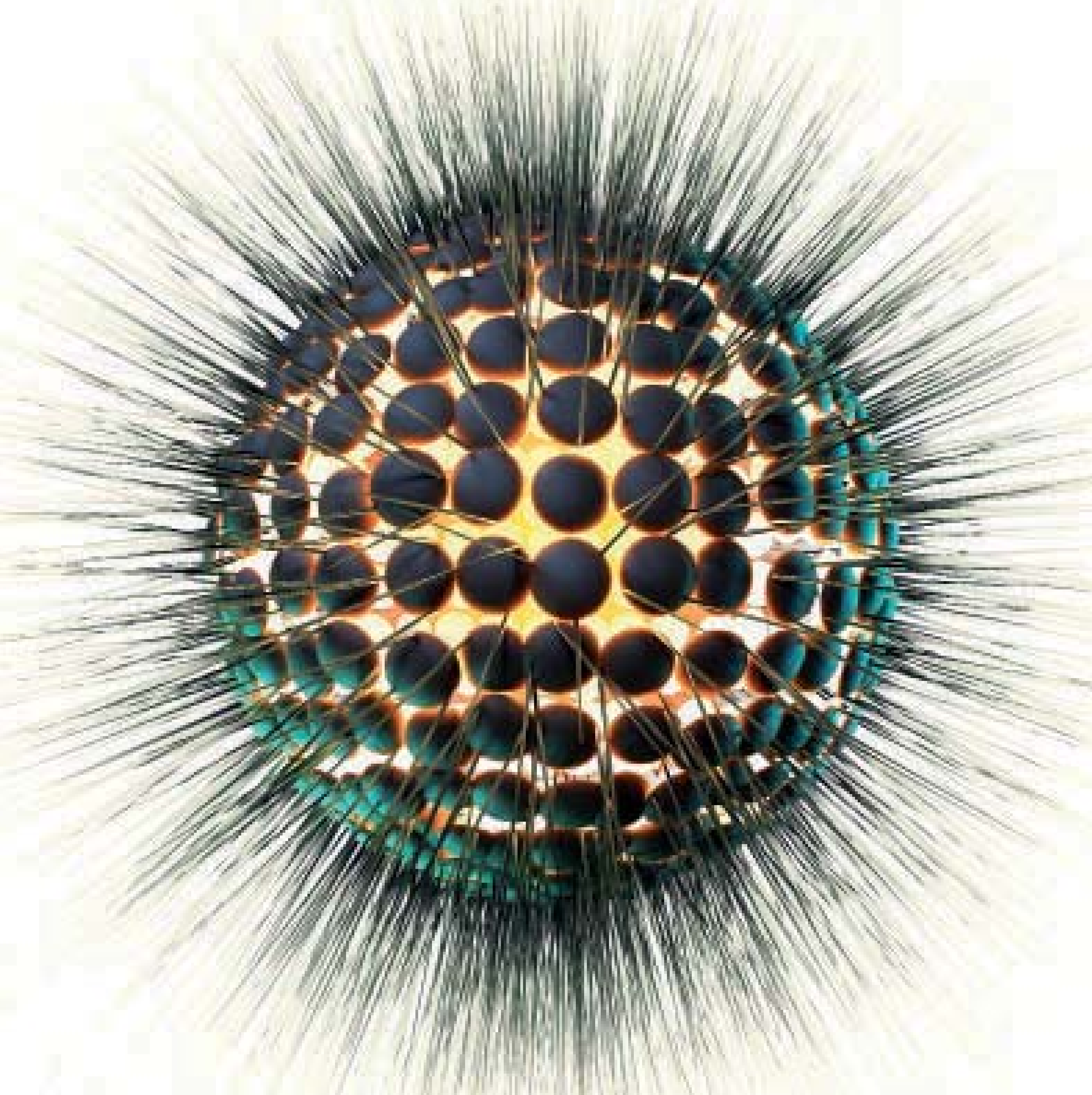
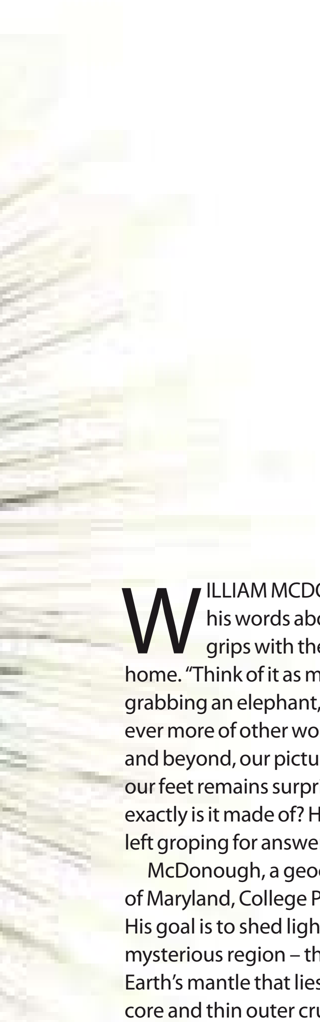
COVER STORY



Messengers from the underworld



Messengers from the underworld

Neutrinos escaping Earth's bowels have fascinating tales to tell about our planet – if only we can catch them. Anil Ananthaswamy goes hunting

WILLIAM MCDONOUGH doesn't mince his words about our attempts to get to grips with the lump of rock we call home. "Think of it as many blind people grabbing an elephant," he says. While we learn ever more of other worlds in our solar system and beyond, our picture of the Earth beneath our feet remains surprisingly sketchy. What exactly is it made of? How did it form? We are left groping for answers.

McDonough, a geochemist at the University of Maryland, College Park, aims to change that. His goal is to shed light on the planet's most mysterious region – the vast netherworld of Earth's mantle that lies between its hot central core and thin outer crust. Light, though, is not McDonough's thing: he and his colleagues are planning to get their answers using neutrinos. Implausible as it might sound, these reclusive particles could be just the thing to spill the beans about our planet's past and present. There is just one proviso: we have to catch enough of them first.

It is not that we know absolutely nothing about the elephant below. We know that about 4.6 billion years ago, in an outer spiral arm of the Milky Way, a dense cloud of hydrogen gas and dust began to collapse in on itself. Its centre ignited to make the sun, while farther out grains of dust slowly coalesced to form larger and larger solid bodies. A few million years later, some of them had grown big enough to form rocky planets.

We also know roughly what went into making these planets. The sun is mostly hydrogen and helium, volatile elements that would not contribute much to a rocky planet. But spectroscopic studies of the sun's surface also reveal heavier, less volatile elements, among them oxygen, carbon, iron, silicon, aluminium and magnesium. Meteorites – rubble left over from the planetary construction works – periodically rain down on us and contain a broadly similar inventory. These materials, then, are the substance of our planet.

What lies beneath

But how much of each element is there, and where are they? Studies of the planet's magnetic field, and of seismic waves passing through Earth's core, indicate that it is a partially molten mix of iron and nickel. Various scratchings and scrapings of Earth's outermost crust show it consists mostly of various oxide and silicate minerals (see diagram, page 35).

So far, so good. But what lies between core and crust, in the huge bulk of Earth's mantle? The mantle makes up about two-thirds of the planet's total mass. Knowing its composition would improve immeasurably our idea of Earth's chemical inventory and give us clues about conditions when it formed. Depending on the surrounding temperature, subtly varying amounts of different elements would have condensed out of the solar nebula into solid matter. Knowing how those elements are spread in the mantle now – homogeneously, in patches of different compositions or in layers – will also tell us whether the whole mantle is a churning mass constantly redistributing matter and heat. This would give us a better handle on what drives processes such as plate tectonics and volcanism.

Clues about the mantle's composition are currently limited to rock samples ejected by volcanoes or left exposed when portions of tectonic plates fail to slip neatly below one another at plate boundaries. Such rocks are seen in some mountain ranges towards the edges of continents such as the Pyrenees in Europe and the Japanese Alps. But are they representative of the whole mantle or just its uppermost layers? To find out, we need a way of analysing material far beyond the magma chambers of volcanoes or the reach of our drills.

Enter – or rather exit – neutrinos.

Neutrinos are the neutral, near-massless particles that have been in the headlines lately for their do-they-don't-they flirtation with breaking the cosmic speed limit. But they – or more precisely an antimatter variant called electron antineutrinos – are also spewed out in vast numbers by chains of radioactive decays originating with uranium and thorium nuclei, in rocks far down in Earth's interior.

How does this help? Because like silicon and all those other elements, uranium and thorium were present, albeit in smaller amounts, in the solar nebula, and would have condensed out in different amounts at different temperatures. If we knew how

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much uranium and thorium went into making Earth, we would know what these conditions were and could extrapolate how much of everything else we would expect to find inside. By tracing where in the mantle uranium and thorium are distributed, we can also begin to understand our planet's inner machinations. "The key to understanding Earth models is to find out where and how much uranium and thorium are in the mantle," says geophysicist Steve Dye of the Hawaii Pacific University in Kaneohe.

And there is no better way of doing that than by counting the "geoneutrinos" that their decays produce. Because they hardly interact with normal matter, these particles race unimpeded through Earth's interior, allowing detectors near the surface to snag them as they leave.

In principle, at least. In practice, that same flightiness makes neutrinos far more likely to pass through our detectors too. Geoneutrino hunting takes skill and a lot of patience.

Fortunately, we have spent the past decade developing that. The Kamioka Liquid-Scintillator Antineutrino Detector (KamLAND), which came into service near the central Japanese city of Hida in 2002, consists of 1000 tonnes of a transparent liquid solution that, when hit by a neutrino, emits a flash of light. It is situated 1 kilometre down, the better to shield it from cosmic-ray muons, whose signals mimic those of neutrinos.

In 2005, KamLAND saw the first, faint signal of electron antineutrinos from Earth's bowels, but it was drowned in a din of antineutrinos produced by nearby nuclear power plants. In 2007, a detector upgrade and the temporary shutdown of one of the largest plants allowed the signal to shine through. By the end of 2009, KamLAND had recorded 106 electron antineutrinos with the right energy to come from decays of uranium and thorium within Earth.

Meanwhile, the Borexino experiment was also getting glimpses. Situated at the Gran Sasso National Laboratory in central Italy, this smaller detector was built to pick up neutrinos from nuclear processes in the sun. Combining data from the two experiments was enough to produce the first concrete geophysical predictions from geoneutrinos alone: that the decay of uranium and thorium in the mantle and crust contributes about 20 terawatts (TW) to the heat escaping from Earth's interior (*Nature Geoscience*, vol 4, p 647).

These are the sorts of numbers we need if we are to start outlining what lies beneath. Earth radiates about 46 TW of heat through its surface, from two sources: "radiogenic" heat produced in radioactive decays, and "primordial" heat stored up during Earth's formation as particles collided and iron sank to the core. Establishing how much surface heat comes from each source has wide ramifications for our picture of Earth. For example, if material in the mantle is convecting slowly, or in layers with limited heat transfer between them, little primordial heat will be transported from Earth's innards to its surface. If so, the lion's share of Earth's heat flux – 30 TW or more – must be of radiogenic origin. The neutrino experiments suggest the true figure is lower, implying that the mantle is mixing relatively thoroughly.

Hidden puzzles

The radiogenic heat flux also indicates that the planet has an overall uranium content of some 20 parts per billion. Exposed mantle rocks contain similar amounts of uranium, suggesting that they are indeed representative of the mantle, and backing up the idea that the entire mantle is mixing efficiently. But it also hides a puzzle. The exposed mantle rocks are dominated by a magnesium iron silicate mineral, olivine, and their uranium content is appreciably higher than that of a class of meteorite called enstatite chondrites. These meteorites have long been thought to be representative of the material that made Earth, and are dominated by another silicate material, pyroxene. That raises the question of where this pyroxene-dominated material is – hidden in pockets deep in the mantle, perhaps? Or is Earth's composition different from that of enstatite chondrites?

The ratio of olivine to pyroxene in Earth's mantle is crucial to pinning down where and when the planet formed in the solar nebula. Olivine would have precipitated out at a slightly higher temperature than pyroxene, so there would have been more of it closer to the sun, or earlier in the planetary construction process when temperatures were higher.

We are still a way away from the answers. With the numbers of geoneutrinos as yet spotted, there is a lot of wiggle room in the estimate of radiogenic heat flux: the 20 TW figure comes with a quoted error of about ±9 TW, making it hard to discount any scenario of mantle composition or mixing. KamLAND and Borexino alone are unlikely to put the debate to rest. A third detector, due to switch on in 2013, could make a decisive difference.

This is SNO+, situated deep underground at the Sudbury Neutrino Observatory in Ontario, Canada. It is about the same size as KamLAND, but because it is under 2 kilometres of rock, it

INSIDE SOURCES

Confounding sources of neutrinos – from cosmic rays to nuclear reactions in the sun and our own nuclear plants – are wearily familiar to hunters of "geoneutrinos" from within Earth (see main story). But to map goings-on inside Earth's mantle, we also need to rule out neutrinos from Earth's crust and core.

The crust is thin relative to the mantle, but its proximity to underground detectors means its geoneutrino signal can overwhelm the one from the mantle. Yu Huang at the University of Maryland, College Park, is using geological and seismic data to characterise the crust's rock formations right down to the mantle boundary in a region centred on Canada's next-generation SNO+ neutrino experiment. The aim is to estimate how much uranium and thorium is there, and so how many neutrinos their decays are likely to produce. "If we can pound down the uncertainty of the composition of the continental crust in the area around SNO+, we can improve on what would be the signal coming from the Earth's mantle," says William McDonough, Huang's supervisor.

Meanwhile, the core seems to have gone quiet. Not too long ago, geophysicists thought it likely that there was enough uranium in the core to make it a giant nuclear fission reactor. But simulations done by McDonough and his colleagues show that at the high temperatures and pressures found in the magma oceans that filled early Earth, uranium almost exclusively prefers the company of elements found in mantle-like rocks to the iron and nickel of the core (*Geochimica et Cosmochimica Acta*, vol 70, p 1537). Nuclear fission also produces neutrinos that are higher in energy than those produced by the radioactive decay of uranium and thorium. The Borexino experiment at the Gran Sasso National Laboratory in Italy has put an upper limit on such neutrinos from a natural reactor in the Earth's core, attributing at most a comparatively measly 3 terawatts of surface heat to such processes (*Physics Letters B*, vol 687, p 299).

Mantle mysteries

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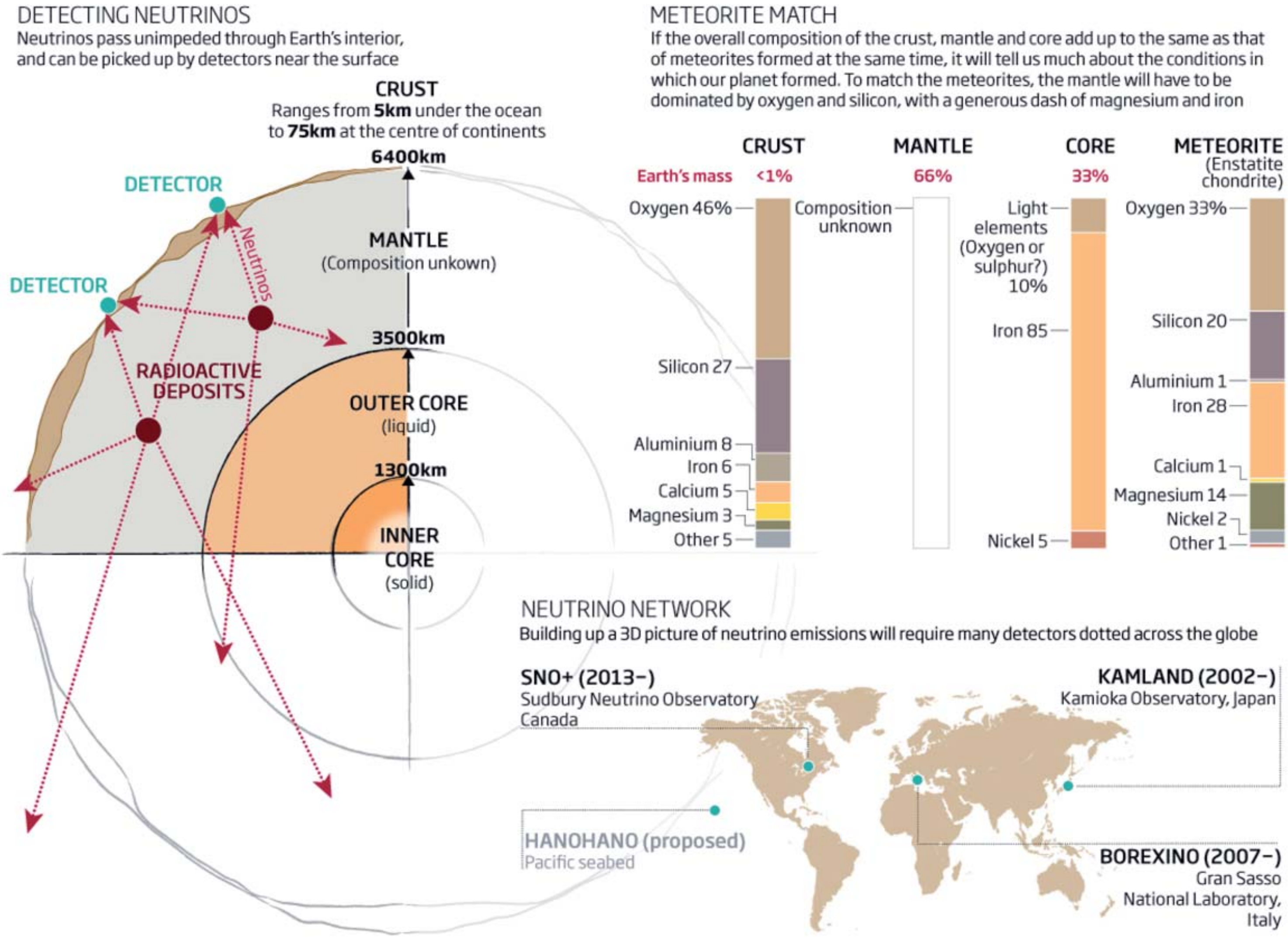
The composition of Earth's mantle, which comprises most of the planet, is unknown. Neutrinos emitted by radioactive deposits within it will tell us how much of each element the mantle is likely to contain and also whether it moves and mixes, or stays solid and stationary



will be better protected from cosmic ray muons. And, says McDonough, "it is not surrounded by a thousand neutrino flashlights": there are far fewer nuclear reactors in Ontario than Japan. With lower background counts, SNO+ should observe geoneutrinos by the bucketful – by neutrino standards, anyway. "It'll probably get 25 geoneutrinos per year," says Dye. Over a few years, that might be enough to shrink the error on the radiogenic heat measurement and start building some certainties.

That is just the beginning. Ideally, we want to map where geoneutrinos come from, and so get a finer-grained picture of the distribution of uranium and thorium and the homogeneity and mixing of the mantle. That means cutting out geoneutrinos from other sources such the crust and core (see "Inside sources", left), and will require a network of detectors looking for neutrinos coming up from different places and at different angles. That would allow us to find out more about peculiar regions of the mantle, such as the "super-plumes" below Africa and the Pacific Ocean that have been invoked to explain anomalous areas of volcanism. The velocity of seismic waves drops dramatically through these regions, which seem to extend from the mantle-core boundary half the way to the surface, suggesting that they are less viscous and perhaps therefore hotter. That might be because they contain larger amounts of decaying uranium and thorium. If so, they should be geoneutrino hotspots.

> "All it takes is one unlikely thing, and our vision of how the planet functions and evolved could change"

An ambitious project proposed by John Learned of the University of Hawaii at Manoa, supported by Dye and McDonough, would help settle such questions. The Hawaiian Anti-neutrino Observatory, or Hanohano, is a detector designed to be taken out on a barge and dropped down to the ocean floor. The water overhead would protect the detector from confounding cosmic-ray muons. What's more, the ocean floor has the thinnest crust, with a uranium content 10 times less than that of the continental crust. A detector there will essentially see a pure mantle signal.

That is for the future, but geoneutrinos offer some answers for the taking. "All it would take is for us to find one seemingly unlikely thing, and it could change our vision of how the planet functions and has evolved," says Learned. And what is true for one planet in an undistinguished spiral arm of the Milky Way could also inform our ideas of how similar planets formed elsewhere, and under what conditions. Reason enough to let neutrinos loosen our blindfolds, and give us a better view of this planetary elephant of ours. n

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