Selected Article

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Fire down below

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Could we be standing above an untamed nuclear reactor nearly 10 kilometres across? There's only one way to find out, says Stephen Battersby

SOON we will be able to see into the centre of the Earth. Giant detectors will let us look down through the crust, the rocky mantle and the iron core. And there, thinks Marvin Herndon, we will see an enormous nuclear reactor, an 8-kilometre ball of fissioning uranium and plutonium.

Herndon is an independent geophysicist based in San Diego, California. For years, his georeactor idea has been shrugged off as a wild guess, but now physicists are devising machines that will find out whether Herndon is right or wrong. Either way, they should answer a question that no one has yet managed to resolve: what is generating the intense heat that exists in the inner core of the Earth?

Though controversial, Herndon's answer is simple enough. For starters, uranium is an exceptionally heavy element, so when the Earth was young and molten, he reasons, most of its uranium would have sunk to the centre of the planet (see "A heart of uranium?"). There would have been enough to gather into a ball several kilometres across, forming a huge natural nuclear fission reactor.

We know natural reactors can exist. One burnt on Earth about two billion years ago at Oklo in Gabon, west Africa, when uranium in the crust became concentrated enough to trigger a controlled chain reaction. Could the same thing happen on a vast scale at the core?

That could certainly explain another mystery: the fact that our planet is producing more heat than anyone can account for. Most physicists believe the Earth's magnetic field is generated by a dynamo of churning liquid iron in the outer core. But it takes some kind of heat source to drive the convection currents, like a hotplate under a pan of water. Some heat almost certainly comes from liquid iron and nickel in the outer core crystallising to join the solid inner core. However, most Earth scientists now think this won't be enough to power the dynamo, so some researchers speculate that the core might contain radioactive elements such as potassium-40, which generate heat as they decay. But Herndon's georeactor, if it exists, could power the dynamo.

How can we tell who is right? There are more than 6000 kilometres of rock and metal between us and the centre of Earth: something of a barrier to exploration. Not an insurmountable one, however. We may not be able to journey to the centre of the Earth, but other things can travel out - among them subatomic particles called antineutrinos, which fly through rock and metal as easily as a javelin through air. Antineutrinos are produced during radioactive decay, so the georeactor's waste would be a powerful source.

In the past few years, physicists have become much better at building detectors to spot antineutrinos. Even though these particles are elusive, if you build a big enough detector and there are enough antineutrinos flying through, then every now and then one will hit something and show up.

"Liquid scintillator" detectors use vast underground chambers filled with water or another fluid. An antineutrino might hit a proton in the water and produce a positron and neutron. The positron ionises molecules in the fluid, making it scintillate, or flash. The neutron briefly continues on before being captured by another atomic nucleus, which then decays, causing another flash. The two flashes happen almost at the same time: the telltale signature of an antineutrino.

Already, physicists have seen antineutrinos from inside the Earth. In 2003, scientists at the KamLAND detector in Kamioka, Japan, reported seeing nine antineutrinos with energies that showed they were probably emitted by radioactive isotopes somewhere in the planet. But KamLAND was unable to determine their exact origin. To zero in on the core, you need a detector with a sense of direction, one that can trace the path of incoming antineutrinos back to their origin. When a neutron is created inside a liquid scintillator, it initially travels in the same direction as the antineutrino. By pinpointing the positron and neutron flashes, you can join the dots to find the original particle's path.

Unfortunately, this won't work in current detectors. The neutrons wander far from their original course before they get absorbed, so the line between the two flashes often does not point in the same direction as the path of the original antineutrino. To solve this problem, one plan is to lace the detector fluid with gadolinium. "Gadolinium is big and fat and loves eating neutrons," says Brian Fields of the University of Illinois at Urbana-Champaign. It mops them up quickly before they have had time to wander off course, so the antineutrino's path can be pinned down.

Fields is part of a group that wants to put gadolinium trichloride into the SNO antineutrino detector near Sudbury in Ontario, Canada, so that it can be used to map sources of antineutrinos in the Earth.

Once SNO has shown that the method works, a larger gadolinium scintillator should be able to give us a blurry picture of radioactivity in the core, Fields says. He would be especially keen to see antineutrinos from isotopes such as uranium and potassium-40. Enough of these spread throughout the core could provide the heat to drive the dynamo. We would have found the ultimate source of our magnetic field.

But such a detector could also test the georeactor theory by looking at the energy spectrum of antineutrinos from the core. The many waste products of the georeactor would produce a much broader spread of energies than decaying uranium or potassium alone.

However, a more exotic machine could give us an even sharper picture of the core. Rob de Meijer of the University of Groningen in the Netherlands has sketched out an idea for what he calls a neutrino antenna. The plan is to drill a hole into the Earth just 30 centimetres wide but up to 6 kilometres deep, and then at the end of that main shaft to drill a set of radiating sub-shafts. "It looks like an upside down, blown-out umbrella," says de Meijer. Long, thin, fluid-filled detectors would be installed in the shafts and, with enough of them pointing in different directions, the antenna could have very sharp vision.

De Meijer hopes that using available drilling technology would make such antennas relatively cheap, perhaps only 50 to 60 million euros. He has already chosen a site on the Caribbean island of Curaçao, which is far away from any man-made reactor and whose rocks are low in natural radioactivity. This would make it easier to pick out any signal from the Earth's core.

The final word on the georeactor will have to wait for one of these planet-probing machines, but Herndon thinks he has at least one good piece of evidence to back up his theory in the meantime: traces of gas in Earth's rocks. This clue came from simulations run by Daniel Hollenbach, a nuclear expert at Oak Ridge National Laboratory in Tennessee. He believes that a georeactor could make its own fuel, like man-made fast breeder reactors.

In a fast breeder, plutonium, uranium-238 and other uranium isotopes are mixed together, and the reactions between them "breed" more fissionable plutonium. If the georeactor is a fast breeder it could keep going for more than five billion years, with a power output of 3 terawatts (*Proceedings of the National Academy of Sciences*, vol 98, p 11085). And that means Herndon's georeactor could keep running for the 4.6-billion-year lifespan of the Earth, contrary to what critics have claimed. "Nobody believed that you could keep a reactor running at that power for that length of time," says Hollenbach.

And there's a bonus. One of the by-products of fission is helium. It comes in two stable isotopes: the common variety, helium-4, and the rarer helium-3. Hollenbach's simulations show that the georeactor generates these two types of helium in a particular ratio, which roughly matches the helium ratio measured in helium from fresh volcanic rocks on Earth. So if you find yourself near a volcanic spring or vent, have a sniff - you might be smelling the georeactor. "It's a knock-your-socks-off kind of result, the first convincing evidence that there is a georeactor," says Herndon.

It doesn't convince most of his peers, however. The conventional view is that the helium-3 in surface rocks is simply left over from when the planet formed, while the helium-4 comes from the radioactive decay of uranium and thorium in the mantle. Herndon claims that his idea fits the data better. Newer volcanic rocks, such as those in Iceland and Hawaii, contain a higher proportion of helium-3 than older rocks, and the simulation shows that the georeactor also makes a higher proportion of helium-3 as it ages.

None of this impresses David Stevenson, an expert on planetary structure based at the California Institute of Technology in Pasadena. Stevenson is not allergic to provocative ideas - he has even devised a scheme for sending a probe to the core of the Earth using molten iron to drive a crack through the mantle - but he has little time for the georeactor. "If you have a profound puzzle, scientists are more willing to accept outrageous solutions," he says. "But there is nothing profoundly mysterious about the helium-3 or the magnetic field. They don't seem to require a major rethink. There is no need for an extraordinary explanation."

Herndon is undaunted by such criticisms, and thinks a georeactor might answer some other questions too. Fluctuations in the georeactor's power could explain why the Earth's magnetic field is so fickle, shutting off and reversing every few hundred thousand years. The georeactor could be responsible for catastrophic tectonic events in the planet's past, he says. He even speculates that it could have something to do with El Niño.

And it doesn't end on Earth: Herndon believes that reactors generate the heat of Jupiter, Saturn and Neptune, and suggests that nuclear fission might kick off fusion reactions in baby stars. If he is right, without his reactors the whole universe would be dark and dull.

Notions like these seem far-fetched to most scientists, tarnishing the georeactor theory. Even so, no one is saying that Herndon's big idea is impossible. In a few years' time, physicists might get a picture of the Earth's inner core. If they do, perhaps they will see the georeactor shining up at them like the Earth's second sun.

A heart of uranium?

Nobody disputes that there was a lot of uranium in the young Earth, enough to form Marvin Herndon's georeactor. The only question is, would it gather into a lump in the centre of the planet, to let a chain reaction begin?

In the standard picture, the Earth was formed out of stuff similar to a common kind of meteorite called ordinary chondrites. As the planet grew, heat melted this raw material and the rocks and metals began to separate. The metals, mainly iron and nickel, sank to form the core, while the lighter rocks floated up to become the mantle and crust.

Uranium tends to combine chemically with oxygen to form compounds that are "lithophilic", that is, they tend to accumulate in rock. So according to the majority of geophysicists, all the uranium would have been mopped up by the rocky mantle and crust.

Unless, of course, there wasn't much oxygen around. Herndon thinks that most of the raw material for our planet was more like another kind of meteorite, called enstatite chondrites, which are low in oxygen. Such meteorites are quite rare on the whole, but Herndon points out that they are more common in the inner solar system where Earth formed. In a young planet starved of oxygen, most of the uranium would combine with sulphur instead: that uranium sulphide would dissolve in the molten metal and head to the core.

David Stevenson of Caltech doesn't rule out the possibility of uranium in the core, but he doesn't believe it would have sunk to the centre. "Even if you put uranium in the core, it is immensely diluted. It's not going to separate out at those high temperatures - it will stay mixed. I'm not saying that the georeactor is impossible; but if it's true, it's lucky, because the reasoning that led to the idea is incorrect." Herndon, however, thinks that other chemicals could help uranium sulphide precipitate out of the liquid iron. It could then form into balls and rain down to the centre of the core.

Stephen Battersby