

GEOPHYSICS

Mapping the Earth's Engine

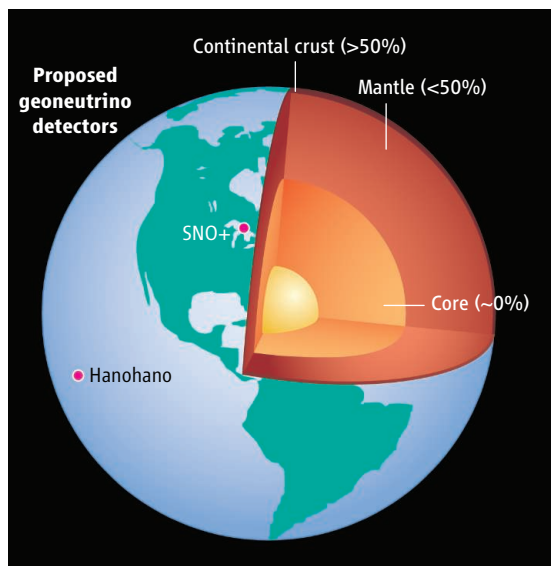
William F. McDonough

Particle physicists and geophysicists rarely meet to compare notes, but earlier this year researchers from these two disciplines gathered to discuss antineutrinos (the antiparticle of the neutrino) (1). These fundamental particles are a by-product of reactions occurring in nuclear reactors and pass easily through Earth, but they are also generated deep inside Earth by the natural radioactive decay of uranium, thorium, and potassium (in which case they are called geoneutrinos). Particle physicists have recently shown that it is possible to detect geoneutrinos and thus establish limits on the amount of radioactive energy produced in the interior of our planet (2). This year's joint meeting was aimed at enhancing communication between the two disciplines in order to better constrain the distribution of Earth's radioactive elements.

Researchers from the Kamioka Liquid scintillator Anti-Neutrino Detector (KamLAND) in Japan reported results that are consistent with the power output produced from the decay of thorium and uranium (16 TW), and the abundances of these elements in Earth, as estimated by geoscientists (3). (Potassium geoneutrinos cannot be detected at present due to the high background in this region of the spectrum.) The initial measurement is also broadly consistent with the Th/U ratio for Earth being equal to that of chondritic meteorites, which is a fundamental assumption used by geochemists to model planetary compositions. However, the upper power limit determined by the experiment (60 TW at the 3σ limit) exceeds Earth's surface heat flow by a factor of 1.5 and is thus not very useful as a constraint for the models.

Nevertheless, there is great excitement within the two communities, as advances in antineutrino detection are anticipated. The KamLAND detector was intentionally sited near nuclear reactors in order to characterize antineutrino oscillation parameters (the reactor produces so-called electron antineutrinos, and antineutrinos can oscillate between the three different "flavors"—the electron, muon, and tau antineutrinos)—and sense fluctuations in reactor power output. Consequently,

The author is in the Department of Geology, University of Maryland, College Park, MD 20742, USA. E-mail: mcdonoug@umd.edu



Inside story. One model of the distribution of radioactive elements potassium, thorium, and uranium in Earth. New antineutrino detectors in Canada (SNO+) and Hawaii (HANOANO) should allow more precise determination of these distributions.

the reactor signal overwhelmed the geoneutrino signal. New detectors are being developed, deployed, and positioned in locations that have substantially smaller contributions from nuclear reactors, and thus will provide more precise measurements of neutrinos and antineutrinos to both the Earth science and astrophysical communities.

In addition to detecting geoneutrinos, these facilities are designed to detect neutrinos from supernovae and determine their oscillation properties (like antineutrinos, neutrinos can oscillate among their three different states). As particle physicists continue to count geoneutrinos, the signal-to-noise ratio will improve and, with more counts, the uncertainty in the radioactive energy budget of Earth will shrink and the measured Th/U ratio of the planet will be determined to a greater precision. Measurement uncertainties of 10% or better are possible with the new detectors, and are achievable with only 4 years of counting.

What does this mean for the Earth sciences? Geoneutrino detectors will be sited on continental crust of different ages, including ancient cratons, the oldest pieces of continents (see the figure). One proposal is to convert the Sudbury Neutrino Observatory (SNO) to "SNO+" (4). This 1000-ton detector is sited in a mine in Ontario, Canada, and represents an

Neutrinos created by nuclear decay may allow geoscientists to measure the distribution of radioactive elements in the Earth.

optimal location for measuring the distribution of heat-producing elements in the ancient core of a continent. Here, the antineutrino signal will be dominated by the crustal component at about the 80% level. This experiment will provide data on the bulk composition of the continents and place limits on competing models of the continental crust's composition. The Boron Solar Neutrino experiment (Borexino) detector, situated in central Italy (and hence somewhat removed from the regions of France with many reactors), has begun counting (5). This detector will accumulate a geoneutrino signal from a younger continental region and surrounding Mediterranean ocean basin, thus receiving a greater proportion of its signal from the mantle.

Particle physicists from Hawaii and their colleagues from elsewhere in the United States, Japan, and Europe are proposing a 10,000-ton, portable geoneutrino detector that is deployable on the sea floor. This detector, called Hawaii Antineutrino Observatory (HANOANO, which is also Hawaiian for "magnificent"), would allow the measurement of the geoneutrino signal coming almost exclusively from deep within Earth, far removed from the continents and nuclear reactors (6). Thanks to the capability of multiple deployments, this detector would provide the exciting possibility of obtaining signals from different positions on the globe.

Ultimately, these different detectors will allow Earth scientists to test various models for the vertical and lateral distribution of thorium and uranium in Earth and will yield unparalleled constraints on the composition of the continents and the deeper Earth. Insights from geoneutrinos will also allow us to decide among competing models of Earth's interior. Decades of research on the state of mantle convection have assumed wide-ranging values of the Urey ratio, the proportion of radioactive energy output to the total energy output of the planet. Geochemists have deduced a Urey ratio of ~0.4, whereas geophysicists prefer constructing mantle convection models assuming higher Urey ratios that

range up to 1.0 (7). In addition, geoneutrino data, coupled with local heat-flow data, will be used to evaluate models of bulk continental crustal composition. Competing models differ by almost a factor of 2 in their concentrations of potassium, thorium, and uranium, with some models critically dependent on heat-flow data (8).

Beyond determining the amount and distribution of heat-producing elements in Earth, particle physicists at the workshop described future experiments, only a decade or so away from implementation, that would allow more precise determination of Earth's structure. Dispersion of neutrino beams penetrating Earth are a function of the electron density of different layers of the planet. The Earth's core,

composed of high-density metal, has a markedly higher electron density than the silicate shells of Earth. Likewise, there is a marked contrast in electron density for the inner and outer core. Measurement of neutrino dispersion in these layers would substantially improve our knowledge of the absolute radius of the core and hence the precision of global seismological models. Such beam studies could also place limits on the amount of hydrogen in the core.

The range of novel experiments underway and those just over the horizon will directly interrogate the interior of Earth in exciting and unparalleled ways (9); these tools will essentially provide new ways of "journeying" to the center of the Earth.

References

1. Deep Ocean Anti-Neutrino Observatory Workshop, Honolulu, Hawaii, 23 to 25 March 2007, www.phys.hawaii.edu/~sdye/hano.html.
2. T. Araki *et al.*, *Nature* **436**, 499 (2005).
3. W. F. McDonough, in *The Mantle and Core*, R. W. Carlson, Ed. (Elsevier-Pergamon, Oxford, 2003), vol. 2, pp. 547–568.
4. M. J. Chen, *Earth Moon Planets* **99**, 221 (2006).
5. M. G. Giammarchi, L. Miramonti, *Earth Moon Planets* **99**, 207 (2006).
6. J. G. Learned, S. T. Dye, S. Pakvasa, in *Proceedings of the XII International Workshop on Neutrino Telescopes*, M. Baldo-Ceolin, Ed. (Istituto Veneto di Scienze, Lettere ed Arti Padova, 2007), pp. 235–269.
7. T. Lyubetskaya, J. Korenaga *J. Geophys. Res.* **112**, B03212 (2007).
8. R. L. Rudnick, S. Gao, in *The Crust*, R. L. Rudnick, Ed. (Elsevier-Pergamon, Oxford, 2003), vol. 3, pp. 1–64.
9. N. H. Sleep, *Earth Moon Planets* **99**, 343 (2006).

10.1126/science.1144405

ENGINEERING

Privacy By Design

George Duncan

Information privacy used to come by default, mainly because of the high costs imposed on any snooper. Yet today, technology has lowered the costs of gathering information about individuals, linking personal details, storing the information, and broadcasting the results. Inexpensive networked surveillance cameras capture our digital image across time and place. Terabyte RAID (redundant array of independent disks) drives provide cheap storage. Real-time data integration software turns fragmented personal data into composite pictures of individuals (1). Communication that is universal, instantaneous, unlimited in capacity, and free for all (2) is becoming ever more plausible.

With cost barriers lowered for data capture, storage, integration, and dissemination, our privacy is no longer implicitly protected (3). Instead, those charged with protecting information privacy must now give it explicit attention. This is the purpose of two thought-provoking reports released this year (4, 5).

In its report, the U.S. National Research Council recommends that fair information practices be adopted by businesses in the use of personal information and that mechanisms be developed to give individuals more control over the use of their information (4). Perhaps the most controversial recommendations involve increased privacy regulation: the



establishment of a Federal Privacy Commissioner or Privacy Commission, greater federal regulation of businesses that use personal information, and more government action to protect individual information privacy.

The report from the U.K. Royal Academy of Engineering emphasizes that, because of human rights law, organizations maintaining systems that use personal information should be accountable for designing them to provide privacy (5). The report recommends less intrusive data use (such as preferring client authentication—"are they valid users?"—over identification—"who are they?"), research on how camera surveillance can ignore law-abiding activities, developing clarity about privacy expectations, formation of trusted third-party organizations as guardians of personal data, and making data collection and use transparent to the data subject. It

New technologies are being developed to protect the privacy of individuals in today's information society.

advocates strengthening the powers of the U.K. Information Commissioner to include substantial penalties for misuse of data.

There are many important reasons to use personal information. For example, under Megan's Law, Web sites permit the public to locate and identify convicted sex offenders in the United States. Depersonalized data on patient drug use can be mined to better target marketing efforts for pharmaceuticals; this approach is used, for example, by Verispan (6). Web-based social networks like Jaiku or Twitter facilitate peer-to-peer exchange of personal details. Road tolls can be debited electronically from a driver's personal account while monitoring every vehicle's speed and recording safety violations.

But in the wrong hands, this personal information can be used to exploit or harm individuals; for example, released sex offenders may be subject to harassment, employers may discriminate against those with certain medical conditions, children on social networks may be targeted by those with evil intent, and car owners may be held accountable for what thieves may do with their cars.

To help balance privacy concerns and the need for personal data, a new paradigm is emerging, in which system designers conduct privacy risk assessments and incorporate privacy as a fundamental design parameter. As Alan Greenspan has remarked (7), "The most effective means to counter technology's erosion of privacy is technology itself." To illustrate how privacy-enhancing technologies

The author is at the H. John Heinz III School of Public Policy and Management, Carnegie Mellon University, Pittsburgh, PA 15213, USA. E-mail: gd17@andrew.cmu.edu