EOS
EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 89 NUMBER 44
28 OCTOBER 2008
PAGES 433–444

Message From Fred Spilhaus to AGU Members

PAGE 433

My service as AGU's executive director will end in mid-2009. I understand the Union is committed to a worldwide search for my successor. My contract ends on 30 June 2009, after which I anticipate stepping into an emeritus status. I have indicated my willingness to serve, at the Union's request, in whatever capacity necessary to assure a smooth transition and the continuing growth and success of AGU.

I am confident that AGU can count on the support of all members so that our Union will continue to flourish as one of the world's preeminent scientific societies. I hope to continue through my life to support the Union in whatever ways I can. And to the extent I am left with time and energy, I will seek other opportunities to use my knowledge and ingenuity to further science.

I wish to thank all of the staff and members for your support and contributions to the outstanding success we have had over my tenure. This is also a time for all of us to remember my predecessor, Waldo Smith, who established the foundation of programs and values on which we together have built this success.

—FRED SPILHAUS, Executive Director, AGU

(For more on the growth of AGU, see the About AGU *section on page 435.)*

Geoneutrino Measurements and Models Investigate Deep Earth

PAGES 433–434

Two underground detectors, in Japan and Italy, are currently recording interactions of highly penetrating particles called geoneutrinos, which are naturally produced inside the Earth. By measuring the geoneutrino flux, these pioneering projects along with several other projects that are being planned are advancing constraints on the contribution of radioactive elements to Earth's heat budget in a novel way. The detector in Japan, which has been in operation the longest, now measures the geoneutrino flux with precision better than a model prediction. Future projects dedicated to measuring and modeling the planet's geoneutrino flux would define the amount and distribution of heat-producing elements in the Earth and provide transformative insights into the thermal history and dynamic processes of the mantle.

Geoneutrino measurements provide experimental evidence for the quantity and distribution of radioactive elements internally heating Earth. Radiogenic heating helps power plate tectonics, hot spot volcanism, mantle convection, and possibly the geodynamo. Information on the extent and location of this heating better defines the thermal dynamics and chemical composition of Earth. Given the enormous technological challenges for directly sampling deep-Earth reservoirs, remotely sensing radioactive elements with geoneutrinos may furnish the first access to this information.

Geoneutrinos are electron antineutrinos emitted in the beta decay of long-lived terrestrial isotopes and their daughters [*Fiorentini et al.*, 2007]. Isotopes contributing significantly to terrestrial heating are

BY S. T. DYE, W. F. MCDONOUGH, AND J. MAHONEY

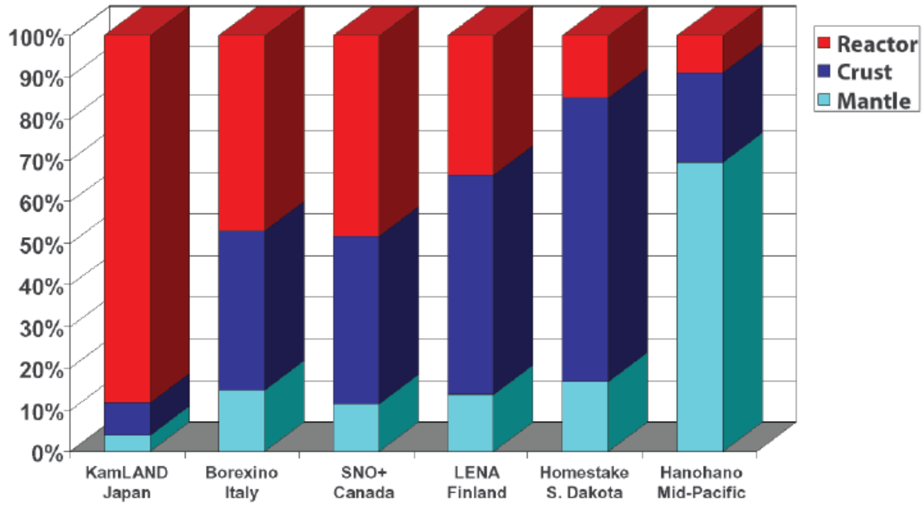

Fig. 1. Predicted antineutrino flux from nuclear reactors, crust, and mantle at project sites.

uranium-238, thorium-232, and potassium-40. Neutrinos and their antiparticles, antineutrinos, uniquely experience only the weakest two of nature's four known forces: gravity and the weak nuclear force. This allows them to pass through Earth with merely the slightest probability of interacting with terrestrial matter. Geoneutrino interactions in massive, subsurface detectors provide information about terrestrial heat sources otherwise inaccessible to geological instruments.

The detection of geoneutrinos typically entails using the inverse-beta coincidence, in which an electron antineutrino and a free proton react to produce a positron and a neutron. This transformation presents two signals coincident in space and time. Initially, the positron and its rapid annihilation with an atomic electron provide a measure of the electron antineutrino energy. Subsequently, a nearby atomic nucleus captures the wandering neutron, releasing a fixed amount of energy. Because the positron and neutron are more massive than the electron antineutrino and proton, the inverse-beta reaction requires electron antineutrinos exceeding a minimum energy threshold. Whereas geoneutrinos from several beta-decaying daughter isotopes of uranium-238 and thorium-232 meet this requirement, those from the beta decay of potassium-40 do not. Present detection techniques are sensitive to geoneutrinos only from uranium and thorium.

Detectors with scintillating liquid as the sensitive medium efficiently record inverse-beta reactions using inward facing photomultiplier tubes, which produce measurable electrical signals from intercepted scintillation light. Physicists operating these detectors underground investigate neutrino oscillations, issues in astrophysics, nucleon decay, and geoneutrinos, and they monitor nuclear reactors. They identify sources of electron antineutrinos by measuring expected fluxes and spectra. Recovering electron antineutrino direction, which would resolve sources and reject background, requires new methods. Background to geoneutrinos comes primarily from nuclear reactors, cosmic rays, and radioactivity in and around the detector. Detectors of high radio purity operating deep beneath the surface, with adequate shielding, and well distant from nuclear reactors are optimal for geoneutrino studies.

Geoneutrino Detection Projects

Two large, underground scintillation detectors are currently recording geoneutrino interactions. The Kamioka Liquid Scintillator Antineutrino Detector (KamLAND), operating since March 2002 in a mine in central Japan with 1000 tons of scintillating liquid, meets its physics agenda by measuring the oscillated spectrum of electron antineutrinos streaming from many nearby nuclear reactors. A recent analysis of KamLAND data estimates the geoneutrino flux with 36% uncertainty when fixing the thorium to uranium mass ratio [*Abe et al.*, 2008]. This estimate does not meaningfully constrain radiogenic heat production; it implies an upper limit greater than the measured terrestrial heat flow. The large antineutrino flux from the nearby reactors and radioactivity inside the detector compete with the geoneutrino signal. However, removal of radioactivity in the scintillating liquid should be complete this year, with more sensitive geoneutrino studies ensuing.

Borexino, operating since May 2007 with 300 tons of scintillating liquid in a tunnel in the Laboratori Nazionali del Gran Sasso, in Italy, meets its physics agenda by measuring low-energy solar neutrinos scattering on electrons [*Arpesella et al.*, 2008]. An analysis of electron antineutrino data including geoneutrinos is in progress. The geoneutrino signal-to-background ratio is expected to be substantially larger for Borexino than for KamLAND due to lower radioactivity and lower flux of antineutrinos from nuclear reactors. Although their locations and sizes are not optimized for geoneutrino investigations, KamLAND and Borexino are pioneering measurements that advance new scientific inquiry and aid future project development.

Scintillation detector projects in the design or planning stage offer opportunities for precision geoneutrino measurements with low background. The next phase of the Sudbury Neutrino Observatory, called SNO+, would operate in a mine in Ontario, Canada, perhaps by early 2011. Comparable in size to KamLAND, it would be the world's deepest geoneutrino observatory and the first situated midcontinent in North America. Another midcontinent project would exploit the low reactor antineutrino flux at the Homestake mine in South Dakota. The Low Energy Neutrino Astrophysics detector, called LENA, is under consideration for operation in a mine in Finland. It would be the largest project, at 50,000 tons of scintillating liquid. The Hawaii Anti-Neutrino Observatory, called Hanohano, is designed for deployment in the deep ocean with 10,000 tons of scintillating liquid. Operating in the tropical Pacific Ocean far from continental crust and nuclear reactors, it would principally observe geoneutrinos from the mantle. Being capable of redeployment at alternate sites, it could potentially measure lateral heterogeneity of uranium and thorium in the mantle. Figure 1 compares the reactor antineutrino flux with a prediction of the geoneutrino fluxes from the crust and mantle at each project site.

Investigating the Deep Earth

Determining the average concentrations of uranium and thorium in the mantle and continental crust is possible by comparing geoneutrino observations at two geologically distinct locations. Whereas a continental observatory would primarily measure geoneutrinos from the continental crust, an oceanic observatory would primarily measure geoneutrinos from the mantle. Observations with Hanohano in the mid-Pacific and a detector with 3000 tons of scintillating liquid operating at Homestake would determine the global uranium content within about 20% uncertainty in 3–4 years [*Dye and Guillian*, 2008]. The period of observation, which is greater for the determination of thorium content, depends on the predicted geoneutrino flux, background, and detection efficiencies. Complementary measurements of geoneutrinos from midcontinental and mid-oceanic detectors would constrain the global content of uranium and thorium.

Geoneutrino flux predictions follow from models of the subsurface distribution of uranium and thorium. According to the commonly accepted model of Earth's history, the planet accreted from a solar nebula. Early core formation removed negligible uranium and thorium from the remaining silicate shell, which then differentiated into the mantle and continental crust. These became the main reservoirs of uranium and thorium today, with each containing roughly equal amounts of these elements. The continental crust, with a mass fraction less than 1% of the silicate shell, has uranium and thorium concentrations that are more than 2 orders of magnitude greater than in the mantle. Crust models identify three subreservoirs, each with different uranium and thorium concentrations. Uncertainties in estimated concentrations typically increase with depth, reaching 30% in the lower crust. The mantle may be relatively homogeneous or contain compositionally distinct subreservoirs, depending on its convection pattern. In addition to an upper mantle depleted of material now in the continental crust, there may be a lower mantle of enriched or less depleted composition. Moreover, a layer highly enriched in uranium and thorium may blanket the core. Revealing the terrestrial distribution of uranium and thorium motivates geoneutrino flux measurements and models.

The two existing geoneutrino flux models are largely the product of physicists [*Mantovani et al.*, 2004; *Enomoto et al.*, 2007]. These models enhance neutrino oscillation studies and enable geological investigations. Models typically establish a budget of uranium and thorium prescribed by a primitive mantle composition. Applying mass balance relationships to estimates of uranium and thorium in various subreservoirs predicts the distribution of these elements and the resulting geoneutrino flux. Although the predictions by both models agree with the recently estimated KamLAND flux, the uncertainty of one prediction [*Mantovani et al.*, 2004] exceeds that of the estimate. Flux predictions of greater precision are necessary to

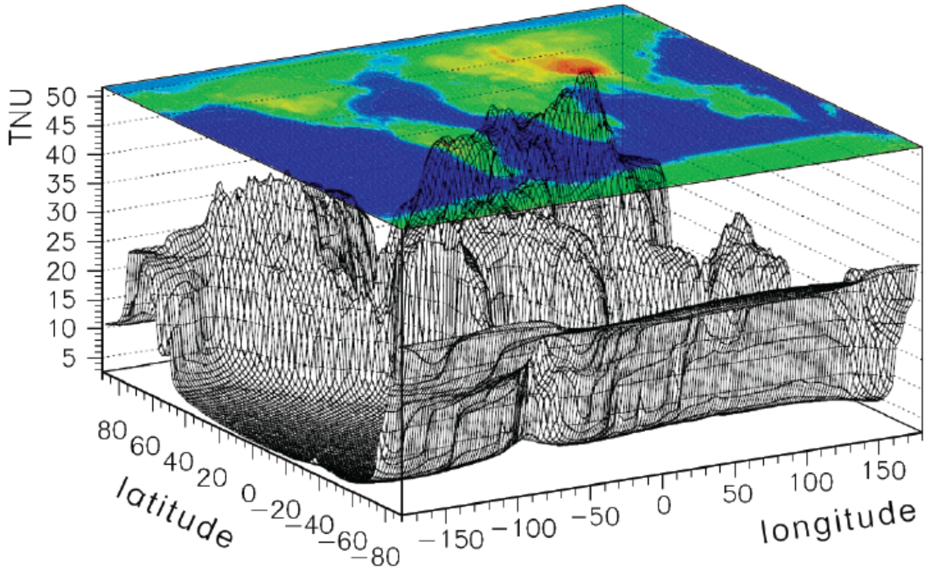

*Fig. 2. Model-predicted geoneutrino signal [*Enomoto et al., *2007] from only the crust in terrestrial neutrino units (TNU). Note that the crust signal in the middle of the Pacific Ocean is just a few TNU. The mantle-only signal predicted by various models ranges from 7 to 22 TNU. A signal in TNU is the number of geoneutrino events obtained from an exposure of 10^{32} free protons, about 1200 tons of scintillating liquid, for 1 year.*

keep pace with experimental progress in geoneutrinos. Figure 2 shows a model prediction for the geoneutrino flux originating only from the crust.

Whereas radiogenic heating of Earth is certain, although imperfectly quantified, heating by natural fission reactors is speculative. Provocatively, proposals suggest that nuclear reactors may exist in or near Earth's core. These georeactors would emit electron antineutrinos just as do human-made nuclear reactors. KamLAND data restrict the power of an Earth-centered georeactor to be less than 20% of the terrestrial heat flow [*Abe et al.*, 2008]. This eliminates some georeactor models [*Rusov et al.*, 2007] yet allows others, including one recently highlighted model that suggests a georeactor at the core-mantle boundary [*Ball,* 2008]. An antineutrino detector operating at a location where the flux from human-made reactors is minimal, such as at Hanohano in the mid-Pacific, would be sensitive to georeactors with power as low as a few percent of the terrestrial heat flow.

Geoneutrino flux measurements from detectors currently operating investigate the quantity and distribution of radioactive elements heating Earth. The precision of a recent flux estimate from KamLAND now exceeds that of a flux model. Experimental constraints continue to improve as detectors accrue exposure. Within several years, SNO+, a new detector that promises significant geoneutrino flux measurements, is likely to begin operations. Larger, strategically placed projects are capable of determining average concentrations of uranium and thorium in the mantle and continental crust. These measured average concentrations combined with detailed modeling of the terrestrial distribution of uranium and thorium, particularly within several hundred kilometers of the detector, would improve the understanding of Earth's thermal dynamics and chemical composition. Developing detection methods sensitive to potassium and geoneutrino direction would further advance these novel investigations of the deep Earth.

References

Abe, S., et al. (2008), Precision measurement of neutrino oscillation parameters with KamLAND, *Phys. Rev. Lett., 100,* doi:10.1103/PhysRevLett.100.221803.

Arpesella, C., et al. (2008), First real time detection of ^{7}Be solar neutrinos by Borexino, *Phys. Lett. B, 658*(4), 101–108, doi:10.1016/j.physletb.2007.09.054.

Ball, P. (2008), Are there nuclear reactors at Earth's core?, *Nature,* doi:10.1038/news.2008.822, 15 May.

Dye, S. T., and E. H. Guillian (2008), Estimating terrestrial uranium and thorium by antineutrino flux measurements, *Proc. Natl. Acad. Sci., 105,* 44–47.

Enomoto, S., et al. (2007), Neutrino geophysics with KamLAND and future prospects, *Earth Planet. Sci. Lett., 258,* 147–159.

Fiorentini, G., M. Lissia, and F. Mantovani (2007), Geo-neutrinos and earth's interior, *Phys. Rep., 453,* 117–172.

Mantovani, F., L. Carmignani, G. Fiorentini, and M. Lissia (2004), Antineutrinos from Earth: A reference model and its uncertainties, *Phys. Rev. D, 69,* 013001.

Rusov, V. D., V. N. Pavlovich, V. N. Vaschenko, V. A. Tarasov, T. N. Zelentsova, V. N. Bolshakov, D. A. Litvinov, S. I. Kosenko, and O. A. Byegunova (2007), Geoantineutrino spectrum and slow nuclear burning on the boundary of the liquid and solid phases of the Earth's core, *J. Geophys. Res., 112,* B09203, doi:10.1029/2005JB004212.

Author Information

Stephen T. Dye, College of Natural Sciences, Hawai'i Pacific University, Kaneohe, and Department of Physics and Astronomy, University of Hawai'i at Manoa, Honolulu; E-mail: sdye@phys.hawaii.edu; William F. McDonough, Department of Geology, University of Maryland at College Park; and John Mahoney, School of Ocean and Earth Sciences and Technology, University of Hawai'i at Manoa, Honolulu