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INTERNATIONAL VIEW POINT AND NEWS

Neutrino geoscience, news in brief

William F. McDonough · Ondřej Šrámek

This issue's "News in Brief" article takes a look at recent emerging research in neutrino geoscience. Geochemist William F. McDonough and geophysicist Ondřej Šrámek from the Department of Geology at the University of Maryland provide considerable insight into the research work and advancements on Earth's heat budget and interior using geoneutrino measurements and models.

The era of neutrino geoscience has arrived. Over the last 10 years, particle physicists have detected the Earth's flux of geoneutrinos, electron anti-neutrinos derived from naturally occurring, radioactive beta-decay events inside the Earth. These elusive, near massless, uncharged elementary particles, which travel at close to the speed of light can tell us about the sources of heat inside the Earth and the planet's thermal history. Electron anti-neutrinos are also useful for revealing the fuel cycle of nuclear reactors and uncovering the details of heavy element production in supernovae. The Earth and its inhabitants are continuously bathed in a flux of geoneutrino, which escape from the Earth at just fewer than 10 million per centimeter squared per second. Matter is mostly transparent to the flux of neutrinos, with most particles having about a 50 % chance of passing untouched through a light year's length of lead (Pb). Technological developments have, however, allowed detection of these ghostly particles via liquid scintillation detectors that are kiloton in scale and sited more than a kilometer underground. By measuring the Earth's geoneutrino flux we are independently determining the abundance and distribution of thorium and uranium inside the planet, which in turn allows us to constrain the amount of radiogenic power driving the Earth's engine.

Identifying and understanding the Earth's energy budget is a fundamental question in geology as it defines the power that drives plate tectonics, mantle convection, and the geodynamo, which, in turn, generates the magnetosphere that protects the planet from cosmic radiation. Through geoneutrino detection, particle physicists have placed limits on the Earth's radiogenic power and demonstrated that it is fueled by more than just radioactivity (Gando et al. 2013; Bellini et al. 2013). The results show that our planet is still using some of its initial inheritance of primordial energy that resulted from the accretion of the planet and the gravitational differentiation of iron sinking to the center of the Earth.

In 2005 the KamLAND team reported the first detection of the Earth's geoneutrino flux (Araki et al. 2005) by recording 25 events over 2 years of exposure. The KamLAND detector is sited deep in the Japanese Alps, opposite Tokyo, on the island of Honshu. Designed to measure the electron anti-neutrino flux from nuclear reactors, this detector is surrounded by $\sim$60 power reactors positioned at different distances and producing a range of energy outputs (a 1 GW reactor radiates about 10^{22} such particles per second). The initial experiment was a great success, as it quickly established that anti-neutrinos, like their matter counterpart, the neutrino, have mass (about 10 million times less than an electron or possibly even lighter, and far less than the other fermions such as quarks and charged leptons), and oscillate between different mass states. It also defined some of the

W. F. McDonough (✉) · O. Šrámek
Department of Geology, University of Maryland, College Park, MD 20742, USA
e-mail: mcdonoug@umd.edu

O. Šrámek
e-mail: sramek@umd.edu

first order attributes of anti-neutrinos by mapping out the fundamental behavior of these leptons.

The Great East Japan Earthquake of March 2011 brought much destruction to Tohoku and surrounding areas and devastated the nuclear reactors at Fukushima Daiichi. As a consequence, all the nuclear reactors in Japan were shut down. Those with minimal damage were slowly brought back online after being checked for safe operation, but later all reactors were once more silenced, which is the state of reactor operations in Japan. For physicists, these changing conditions provided the unexpected bonus of being able to view these various anti-neutrino sources at different mean distances and under different power conditions, ideal circumstances for a thorough physics experiment. For the study of geoneutrinos, it instantly transformed KamLAND into the premier geoneutrino detector with an extraordinary signal to background condition.

The Italian-based Borexino experiment, situated beneath the Apennine Mountains near the town of L'Aquila, began measuring the Earth's geoneutrino flux in 2007. Designed to investigate details of the nuclear fuel cycle in the core of the Sun, which irradiates our surface with a neutrino flux that is $\sim$10,000 times greater than the Earth's geoneutrino flux, this detector readily had an impact on the field of geology given its remoteness from reactors (Italy does not generate power from nuclear reactors) and unprecedented instrumental purity (a critical aspect of background reduction). By 2010 Earth Sciences had its second measurement of the Earth's geoneutrino flux, this time in Italy and at a better than four sigma level of confidence (Bellini et al. 2010).

Much debate in geology surrounds the nature of the Earth's global heat output, which is currently estimated at 46 ± 3 TW (10^{12} W; Jaupart et al. 2007), in particular, what fraction of this power comes from primordial versus radioactive sources? This controversy reaches back more than 150 years to Lord Kelvin, who mistakenly described the Earth's heat loss as that dissipated from a solid that was not undergoing convection and heat transport across boundary layers. Additionally, his formulation of the problem, as noted by Ernest Rutherford, did not include heat from radioactive decay, albeit a lesser influence on the dissipation rate. Today's controversy in geology is best cast in terms of a mantle Urey ratio: the ratio of the amount of radiogenic heat produced in the mantle relative to the total mantle heat loss. This value expresses the driving power of mantle convection in terms of the planet's capacity of internal heating, with competing Earth models suggesting values that range over a factor of more than 20 for the mantle (Šrámek et al. 2013).

Models for the Earth's radiogenic power start with assumptions about the building blocks used to construct the planet, the mode of planet assembly, and the displacement of materials collected during accretion. Although there is a spectrum of planetary models, there are in principle three basic proposals for the amount of heat producing elements—potassium,[1] thorium and uranium (generating 99 % of the planet's radiogenic thermal power)—in the Silicate Earth models (i.e., Earth minus the core). These overarching models are, with increasingly greater power production: (1) the cosmochemical model, (2) the geochemical model, and (3) a traditional geodynamical model (McDonough et al. 2012).

The cosmochemical models have the lowest amount of radiogenic power ($\sim$10 TW). These models construct the Earth from a restrictive group of chondritic meteorites (the most primitive, undifferentiated rocks in the solar system) and/or may include the loss of a thorium and uranium enriched crust due to collisional removal in the earliest days of the solar system. The traditional geodynamical models have the highest amount of radiogenic power ($\sim$30 TW) and use simple physics to describe mantle convection and heat dissipation while maintaining a reasonable fit to the secular cooling record. Such simple models of parameterized mantle convection can be derived from a balance of buoyancy and viscous forces relative to thermal and momentum diffusivities. Later, more developed geodynamical models recognized the role of water in lowering mantle viscosity and the effects of continental blanketing on the thermal evolution of the Earth and required less radiogenic power (as low as 15–17 TW overall). Finally, with the median amount of power production, geochemical models predict about $\sim$20 TW of radiogenic power and are based on mantle samples and constraints from chondritic meteorites, with their limitation being the fraction of the mantle that might be represented by these samples.

None of these competing models are without their detractors and the field is rich with enigmatic observations and conundrums. However, with 7 TW of radiogenic power already locked up in the continents and not contributing to driving plate tectonics and mantle convection, the cosmochemical models predict that primordial, not radiogenic, heat is the dominant energy source for the Earth, leaving only 3 TW of radiogenic power in the mantle. In addition, recent views on the heat flow across the core-mantle boundary envisage a flux of between 10 and 20 TW of power, implying significant basal heating of the mantle and the possibility of radiogenic power in the core. Thus, data from the particle physics community are

[1] K cannot be detected using current technology. This is because hydrogen in the liquid scintillator is the target for the anti-neutrino and the energy needed (1.806 MeV) to convert a proton into a positron and a neutron (i.e., inverse beta decay) is greater than the maximum energy from the potassium geoneutrino (1.311 MeV).

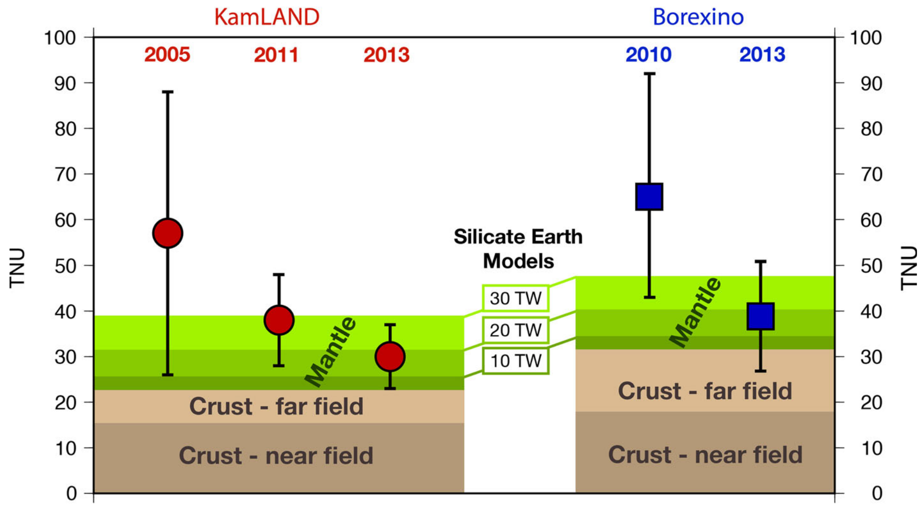

Fig. 1 Results reported from KamLAND (Araki et al. 2005; Gando et al. 2011, 2013) and Borexino experiments (Bellini et al. 2010, 2013) plotted in TNU (Terrestrial Neutrino Unit, defined as one event per 10^{32} target nuclei, the number of H atoms in a kiloton detector per year). Where the original publication did not give results in TNU, a simple recalculation of the reported result was performed. All results shown here are constrained to a Th/U abundance ratio of 3.9. The three Silicate Earth models, cosmochemical, geochemical, and traditional geodynamical, are illustrated here with their limits at 10, 20, and 30 TW total radiogenic powers

welcomed and will ultimately help to resolve these conundrums within the geoscience community.

In 2013, in a first for the biennial Neutrino Geosciences meeting, both the Borexino and KamLAND teams simultaneously reported their newest results demonstrating beyond uncertainties that the Earth is still spending parts of its initial inheritance of primordial energy in addition to burning its radiogenic energy (Gando et al. 2013; Bellini et al. 2013). Although the uncertainties on these measurements are ever improving, error limits still encompass all of the existing models for the Earth. However, this demonstrated that future measurements will bring critical discriminating insights into which models are tenable (Fig. 1). At this 5th meeting of particle physicists and geologists, in which participants shared vastly divergent perspectives in discussing the fundamental energy budget of the Earth, the Borexino team reported a limit on the power from the mantle of 14 ± 11 TW, while the KamLAND team reported their first results from their exceptionally low reactor neutrino background condition.

The future of Neutrino Geoscience is exceptionally bright with a new detector currently coming on line, another in development, and even more planned for the future. In 2014 the SNO+ detector, the re-tasked Sudbury Neutrino Observatory (a major contributor to resolving the solar neutrino problem) will begin counting geoneutrinos, as well as other experimental measurements, on the edge of the ancient stable Superior Craton, which occupies the middle part of the North American plate (Chen 2006). The SNO+ detector will be approximately the size of KamLAND, about twice as large as the Borexino detector, and

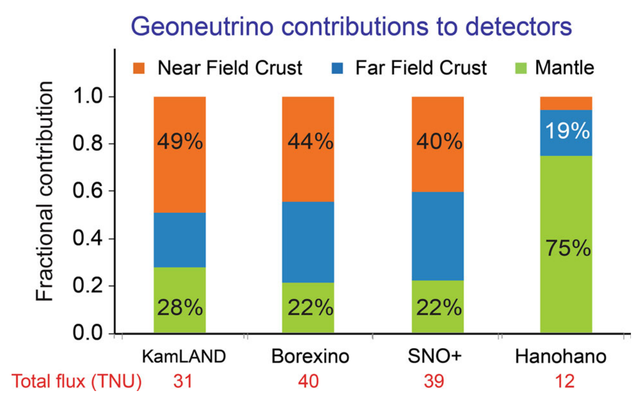

Fig. 2 The relative contributions of geoneutrino counts at various detectors. Data from Table 2 of Huang et al. (2013), with the *Near Field Crust* being the closest ≤500 km radius from the detector, the *Far Field Crust* being all other crust on the globe, and *Mantle* being that from the rest of the silicate Earth. The predicted total flux, in TNU (see Fig. 1 caption for explanation), for each detector is listed at the bottom

will capture a signal that mostly comes from the continental crust. Later this decade the Chinese expect to launch the JUNO experiment, which will initiate a new era of detection ability with a detector that is 20 times larger than KamLAND. However, this detector is dedicated to studying electron anti-neutrinos from reactors and thus will present geoscientists with the challenge of extracting a geoneutrino signal that is only 5 % of the total annual signal. In addition, its shallow overburden depth (700 m) means that it will receive a higher cosmic ray muon flux than the other detectors, presenting a significant problem

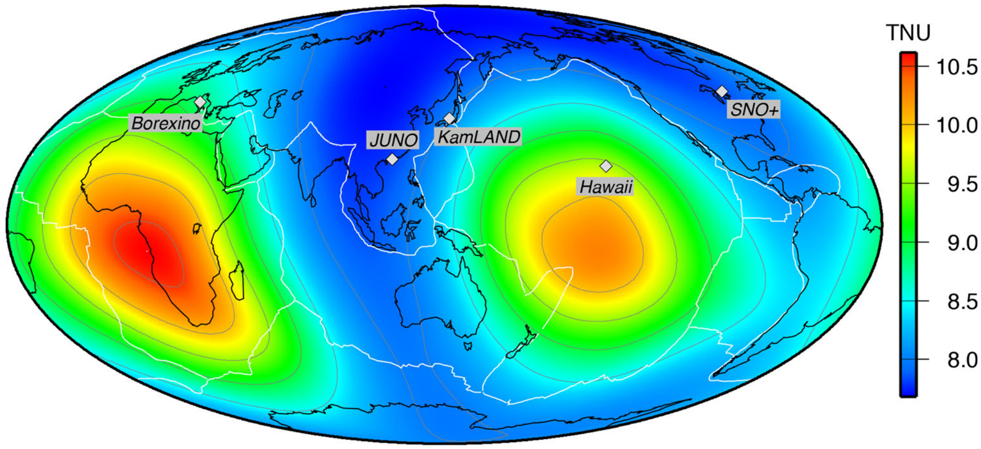

Fig. 3 Global map of geoneutrino flux from ^{238}U and ^{232}Th decay in the Earth's mantle from Šrámek et al. (2013). This flux, as seen from the surface without the crustal contribution is shown in TNU (see Fig. 1 for an explanation). Continental outlines (*black*), plate boundaries (*white*), and locations of geoneutrino detectors are plotted: Kamioka, Japan (KamLAND, operational); Gran Sasso, Italy (Borexino, operational); Sudbury, Canada (SNO+, online 2014); Kaiping, China (JUNO, online 2019); Hawaii (Hanohano, proposed)

for geoneutrino detection at JUNO. All of these detectors, however, are sited on continental crust and as such have a geoneutrino signal that is 75 % crustal and only 25 % from the mantle (Fig. 2). Moreover, uncertainties associated with the present detectors are approximately equivalent to the strength of the mantle signal and thus assessing the mantle contribution is not possible.

There is a growing interest among the geoscience and particle physics communities in the proposed ocean-based detector, Hanohano (Learned et al. 2007). Scaled at between 10 and 50-kilotons, Hanohano would be a mobile detector operating at the bottom of the ocean, with the option to be deployed to obtain remote reactor spectra or placed out in the middle of the ocean, far removed from continental crustal radioactivity, to reveal the nature of heat producing elements in the mantle. This detector would receive 75 % of its signal from the mantle, making it capable of mapping out deep structures therein (Fig. 2). A potential, exciting deployment would place the detector in the middle of the south Pacific, 3,000 km away from South America, Australia, and the core-mantle boundary. This area has been seismologically identified as possessing one of the two major base-of-the-mantle structures that has a strong compositional contrast with its surroundings and is possibly a long-lived, gravitationally anchored reservoir, sourcing upwelling responsible for producing ocean island magmatism.

The idea of mapping the Earth's interior has been a century-long quest of Earth scientists, with 2014 marking the 100th anniversary of the one the science's greatest advances: Beno Gutenberg's discovery of the core-mantle boundary at a 2,900 km depth (c.f., 2,891 ± 5 km; Masters and Shearer 1995). Through Hanohano, we now possess the technology to critically evaluate mantle structures that have been seismologically imaged with a neutrino geoscope that can generate tomographic images of the deep Earth (Fig. 3; Šrámek et al. 2013). Beyond these applications, such an ocean-based detector provides a platform for long base-line neutrino beam experiments and a valuable mobile monitor for nuclear reactor security. Moreover, Hanohano and similar detectors can be used in muon radiographic surveys of underwater and near surface structures, including throats of active volcanoes (Tanaka 2014), and are always prepared to record neutrino waves from supernova sources near and far.

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