GIORNALE DI FISICA VOL. LXIV, Passion for Earth 2022 2023
DOI 10.1393/gdf/i2023-10525-4

# Studying the Earth's radiogenic power with geoneutrinos

V. Strati, F. Mantovani

*Department of Physics and Earth Sciences, University of Ferrara and INFN, Ferrara, Italy*

G. Bellini

*Department of Physics, University of Milan and INFN, Milan, Italy*

**Abstract.** Geoneutrinos, antineutrinos originating from Earth's natural radioactivity, offer insights into the definition of the Earth's heat budget. To date, the KamLAND (Japan) and Borexino (Italy) experiments have both successfully measured the geoneutrino flux. The information was merged to achieve a mantle geoneutrino signal of $8.9^{+5.1}_{-5.5}$ TNU and Earth's radiogenic heat of $20.8^{+7.3}_{-7.9}$ TW, consistent with the $19.7 \pm 3.1$ TW estimated from geochemical Bulk Silicate Models. Future geoneutrino research will involve multi-site mantle analysis, new detectors (SNO+ and JUNO), and advancements in experimental techniques, such as detecting antineutrino directionality and potassium geoneutrinos.

## 1. Introduction

Geoneutrinos are antineutrinos generated by the $\beta^-$ decay of naturally radioactive isotopes inside the Earth, specifically $^{238}$U, $^{232}$Th, and $^{40}$K, all of which have a half-life comparable to or greater than the age of the Earth. As these isotopes decay, they not only produce antineutrinos but also energy, which is referred to as radiogenic heat; consequently, they are known as Heat-Producing Elements (HPEs). The production of antineutrinos and radiogenic heat occurs in a fixed proportion and, therefore, measuring the geoneutrino flux can be used to estimate the amount of radiogenic heat generated by the Earth, providing insights into the inaccessible Earth [1].

The measurement of the geoneutrino flux can be performed by large volume ($\sim$ kton) and high radiopurity liquid scintillator detectors located in underground laboratories to shield the cosmic ray flux. The detection technique is currently the Inverse Beta Decay on free protons, a charged current interaction which makes detectable until now only electron-flavoured antineutrinos of the beta emitters of $^{238}$U and $^{232}$Th chains, given their energy is higher than the threshold reaction (1.806 MeV). The global quantity and distribution of U and Th can be constrained by analysing the energy spectra of geoneutrinos. In addition, by making a precise estimate of the geoneutrino signal produced by the available lithosphere, the mantle component can be disentangled, extracting unique information about the radiogenic power and composition of the Earth.

## 2. The KamLAND and Borexino experiments

To date, the only two experiments able to measure geoneutrinos are KamLAND (Japan) and Borexino (Italy) which claimed their first geoneutrino observations in the first decade of the 21$^{\text{st}}$ century and now gained results with more statistical significance.

KamLAND (Kamioka Liquid scintillator Anti-Neutrino Detector) is a multi-purpose experiment located in the Kamioka mine, $\sim 1000$ m below the summit of Mt. Ikenoyama (Gifu, Japan), *i.e.*, the former site of the Kamiokande experiment. The 1 kton liquid scintillator detector started to collected data in 2002 with the primary goal to detect $\bar{\nu}_e$ from nuclear power reactors and to demonstrate the oscillation nature of neutrino flavor transformation. In the same year, the significant deficit of $\bar{\nu}_e$ from reactors and the oscillatory function of the flavor changing probability, was observed by the experiment [2], while the first experimental study of geoneutrinos was performed in 2005 [3]. The experimental data analyzed here are based on a total live-time of 4397 days (March 7, 2002–April 15, 2018). Adopting a chondritic ratio (Th/U mass = 3.9), the total number of geoneutrinos events is $168.8^{+26.3}_{-26.5}$ corresponding to a signal $S^{\text{KL}}_{\text{Exp}}(\text{U} + \text{Th}) = 32.1^{+5.0}_{-5.0}$ TNU [4].

Borexino is a 278 tons of liquid scintillator detector located in the Laboratori Nazionali del Gran Sasso (Italy) which was designed to measure solar neutrinos starting from their lowest energies. The construction of the detector started after five years of R&D and tests in the detector aimed at the development of innovative methos for the reduction of the scintillator's radioactivity [5]. Thanks to reaching an unprecedented radiopurity ($10^{-18}$–$10^{-19}$ g/g of contaminant concentration), up to now Borexino is the only experiment that succeeded in measuring the entire pp-chain and the carbon-nitrogen-oxygen (CNO) cycles [6,7]. The first geoneutrino measurement was obtained in 2010 with a geoneutrino evidence at $4.2\sigma$ C.L. [8]. The last release of the geoneutrino analysis concerns 3263 days of data taking (from December 2007 to April 2019) that, fixing an *a priori* Th/U ratio mass of 3.9, led to a total of $52.6^{+9.6}_{-9.0}$ geoneutrino events corresponding to a geoneutrino signal of $S^{\text{BX}}_{\text{Exp}}(\text{U} + \text{Th}) = 47.0^{+8.6}_{-8.1}$ TNU [9].

## 3. Studying the Earth with geoneutrinos

The experimental signal measured by the KamLAND ($S_{\text{KL}}$) and Borexino ($S_{\text{BX}}$) experiment are properly combined to indirectly determine the mantle geoneutrino signal, assumed to be the same for both the geoneutrino detectors. In the subtraction of the lithospheric component, a reliable estimate of the crustal component and its uncertainty is mandatory and at the same time the most challenging task. The assessment of the lithospheric signal relies on 3D models of the outer regions of our planet generated through geophysical and geochemical inputs.

The signals of the lithosphere expected at Borexino and KamLAND are modeled as the sum of three components: the Near Field Crust (NFC), the Far Field Crust (FFC) and the Continental Lithospheric Mantle (CLM) (fig. 1). The FFC is the portion of

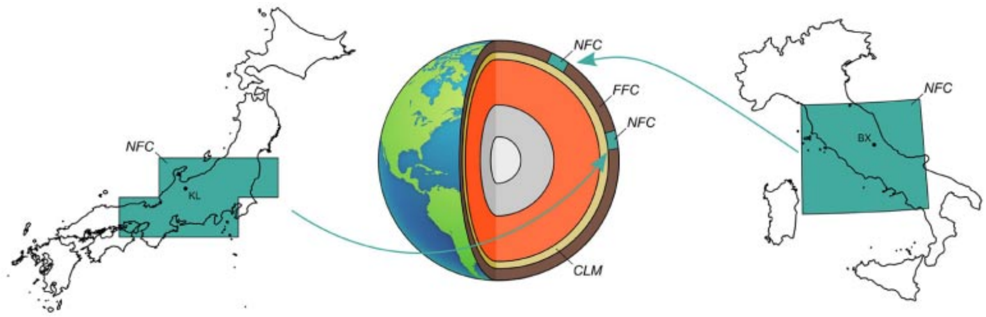


Fig. 1. – Schematic drawing of the Earth's structure with the three components of the expected geoneutrino signal: Near Field Crust (NFC), Far Field Crust (FFC) and Continental Lithospheric Mantle (CLM). Simplified maps of the NFC for KamLAND (Japan) and Borexino (Italy) are shown on the left and on the right, respectively. Not to scale.

crust remaining after the subtraction of NFC while the CLM is the portion of the mantle underlying the continental crust included between the Moho discontinuity and the Lithosphere-Asthenosphere Boundary.

The isotropic $1/4\pi r^2$ spherical scaling factor guarantees that the geoneutrino flux that reaches a detector is mainly influenced by the natural radioactivity present in the vicinity of the detector. A more accurate and reliable signal prediction can be assured with local refined models which implement specific geophysical and geochemical inputs. The NFC are recognized as the 24 voxels ($1° \times 1°$) close to the detectors and the models based on site-specific geophysical and geochemical information of [10] and [11] are adopted to calculate the NFC geoneutrinos signal respectively for KamLAND and Borexino. With the aim to have a coherent mantle signal extraction, the same global lithospheric model [12] is used to predict the FFC and CLM contributions for both experiments (table I).

The mantle signals $S_{\mathrm{M}}^{\mathrm{BX}}(\mathrm{U+Th})$ and $S_{\mathrm{M}}^{\mathrm{KL}}(\mathrm{U+Th})$ can be inferred by subtracting the estimated lithospheric components from the experimental total signals, $S_{\mathrm{Exp}}^{\mathrm{BX}}(\mathrm{U+Th})$ and $S_{\mathrm{Exp}}^{\mathrm{KL}}(\mathrm{U+Th})$:

$$(1)\quad S_{\mathrm{M}}^{\mathrm{BX}}(\mathrm{U{+}Th}) = S_{\mathrm{Exp}}^{\mathrm{BX}}(\mathrm{U{+}Th}) - S_{\mathrm{NFC}}^{\mathrm{BX}}(\mathrm{U+Th}) - S_{\mathrm{FFC}}^{\mathrm{BX}}(\mathrm{U{+}Th}) - S_{\mathrm{CLM}}^{\mathrm{BX}}(\mathrm{U{+}Th}),$$

$$S_{\mathrm{M}}^{\mathrm{KL}}(\mathrm{U{+}Th}) = S_{\mathrm{Exp}}^{\mathrm{KL}}(\mathrm{U{+}Th}) - S_{\mathrm{NFC}}^{\mathrm{KL}}(\mathrm{U{+}Th}) - S_{\mathrm{FFC}}^{\mathrm{KL}}(\mathrm{U{+}Th}) - S_{\mathrm{CLM}}^{\mathrm{KL}}(\mathrm{U{+}Th}),$$

Table I. – *The geoneutrino signals expected at Borexino and KamLAND for the Near Field Crust (NFC), the Far Field Crust (FFC) and the Continental Lithospheric Mantle (CLM) adopted for the mantle signal calculation. Details on calculation methods and uncertainties are report in* [13].

| | KamLAND | Borexino |
|---|---|---|
| $S_{\mathrm{NFC}}$ (U+Th) [TNU] | $17.7 \pm 1.4$ | $9.2 \pm 1.2$ |
| $S_{\mathrm{FFC}}$ (U+Th) [TNU] | $7.3^{+1.5}_{-1.2}$ | $13.7^{+2.8}_{-2.3}$ |
| $S_{\mathrm{CLM}}$ (U+Th) [TNU] | $1.6^{+2.2}_{-1.0}$ | $2.2^{+3.1}_{-1.3}$ |

TABLE II. – *Radiogenic heat ($H_M$) in the mantle and in the BSE ($H$) according to the classes of BSE models and obtained based on the combined geoneutrino measurement. The mantle radiogenic heat for the Poor-$H$, Medium-$H$ and Rich-$H$ models are obtained subtracting from the corresponding value of the BSE the adopted estimates of the lithosphere according to the* [12] *model and considering them linearly independent.*

| | $H_M$ (U+Th) [TW] | $H_M$ (U+Th+K) [TW] | $H$ (U+Th+K) [TW] |
|---|---|---|---|
| Poor-$H$ | $3.2^{+2.0}_{-2.1}$ | $4.2^{+2.4}_{-2.6}$ | $12.4 \pm 1.9$ |
| Medium-$H$ | $9.3 \pm 2.9$ | $11.4^{+3.5}_{-3.6}$ | $19.7 \pm 3.1$ |
| Rich-$H$ | $20.2^{+3.2}_{-3.3}$ | $23.4^{+3.8}_{-3.9}$ | $31.7 \pm 3.4$ |
| Combined KL+BX | $10.3^{+5.9}_{-6.4}$ | $12.5^{+7.1}_{-7.7}$ | $20.8^{+7.3}_{-7.9}$ |

where the three different lithospheric components are considered uncorrelated for KamLAND and Borexino separately. The PDFs of the experimental signals are reconstructed for inferring the mantle signals at KamLAND ($S_M^{KL}(\mathrm{U+Th}) = 4.8^{+5.6}_{-5.9}$ TNU) and Borexino ($S_M^{BX}(\mathrm{U+Th}) = 20.8^{+9.4}_{-9.2}$ TNU).

Assumed the site-independence of the mantle signal, these results can be properly combined in the estimation of a joint bivariate PDF, bearing in mind that i) both experiments assume the same chondritic ratio Th/U mass (3.9) in the extraction of geoneutrino signal and ii) the FFC and the CLM signals are fully correlated. The obtained result ($S_M^{KL+BX}(\mathrm{U+Th}) = 8.9^{+5.1}_{-5.5}$ TNU) is a valuable means of testing the signals expected from diverse compositional models of the Bulk Silicate Earth (BSE), *i.e.*, the present lithosphere and sublithospheric mantle, grouped according to the derived radiogenic heat production ($H$) in i) poor-$H$ models, ii) medium-$H$ models and iii) rich-$H$ models (table II).

A linear relation between the radiogenic heat and the geoneutrino signal is clearly definable:

$$S_M(\mathrm{U+Th}) = \beta \cdot H_M(\mathrm{U+Th}),$$

with the $\beta$ coefficient depending only on the U and Th distribution and ranging between $\beta_{low} = 0.75$ TNU/TW (HPEs' masses are placed in a layer just above the Core-Mantle Boundary) and $\beta_{high} = 0.98$ TNU/TW (HPEs' masses are homogeneously distributed in the mantle). The central value of $\beta_{centr} = 0.86$ TNU/TW is adopted to convert the combined mantle geoneutrino signal into the mantle radiogenic heat ($H_M^{KL+BX}(\mathrm{U+Th}) = 10.3^{+5.9}_{-6.4}$ TW). Summing the well-constrained K contribution ($H(\mathrm{K})/H(\mathrm{U+Th+K}) = 0.17$) [9] and lithospheric radiogenic heat ($H_{LS}(\mathrm{U+Th+K}) = 8.1^{+1.9}_{-1.4}$ TW) [12], the final estimate of the BSE radiogenic heat is $H(\mathrm{U+Th+K}) = 20.8^{+7.3}_{-7.9}$ TW. This result is compatible with the Medium-$H$ models (fig. 2) which assume a bulk major-element composition matching that of CI chondrites, envisaging that the radiogenic heat represents 44% of the global measured heat flux $Q = 47 \pm 2$ TW [14].

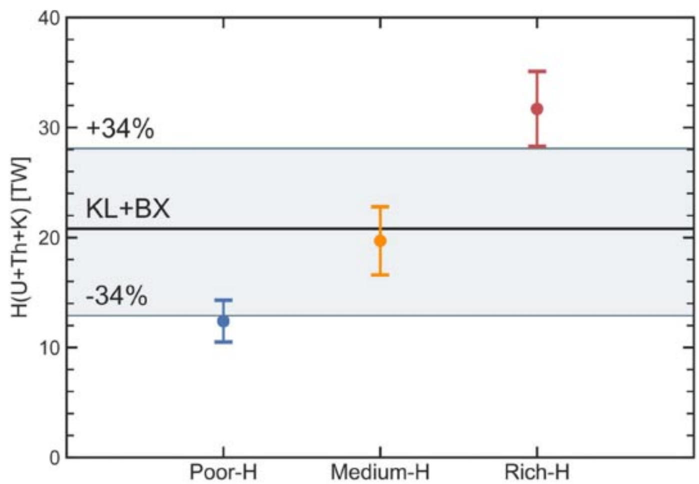


Fig. 2. – Earth's radiogenic heat $H(\mathrm{U+Th+K})$ constrained by the combined geoneutrino measurement of KL and BX compared with the estimates of the Poor-$H$, Medium-$H$ and Rich-$H$ models (table II).

## 4. Looking at the future

The future and unsolved challenges in geoneutrino sciences potentially relies on a multi-site mantle analysis which embeds, in addition to KamLAND and Borexino experimental signals, new data recorded by under construction and proposed detectors. In April 2022 the SNO+ detector [15], a 780 tons liquid scintillator experiment located at the underground SNOLAB facility in Vale's Creighton (Sudbury, Canada), started the scintillator phase projecting itself towards the geoneutrino detection with an expected signal of $S(\mathrm{U+Th}) = 42.9^{+9.2}_{-5.3}$ TNU [16]. An unprecedented statistic ($\sim 500$ geoneutrino events) with a 14% of $1\sigma$ uncertainty is pledged after a year of data-taking of the 20 kton JUNO detector, under construction in the Jiangmen Underground Neutrino Observatory in the Guangdong Province of South China [17]. Two additional experiments were recently proposed by the scientific community: the Jinping neutrino experiment in China [18] and the Ocean Bottom Detector (OBD) [19] in a not yet well defined location in the ocean. Lying on the slopes of Himalaya with the thickest continental crust, Jinping is candidate to have the highest lithosphere contribution ($\sim 84\%$) [20]; the OBD has exactly the opposite case, with the mantle accounting for 70% of the total expected geoneutrino flux and offering a possibility to tighten the constraint on mantle radioactivity abundance and distribution [19].

In a wider perspective it is worth emphasizing that experimental advances, two of all the detection of antineutrino directionality and of potassium geoneutrinos not yet permitted by the current technology, could boost the mantle geoneutrino studies. Indeed, the disentanglement of the lithosphere and mantle contributions could be in principle solved with a direction-sensitive detector, able to map out the Th and U contributions inside the Earth. Moreover, the measurement of K geoneutrinos, translating in an estimate of the K content of the Earth, could offer a unique tool for the comprehension of the behaviour of volatile elements during Earth's early-stage formation.

* * *

The authors would like to acknowledge Kunio Inoue, Kassandra Raptis, Andrea Serafini and Hiroko Watanabe for their valuable support. We would like to express our profound reverence for Prof. Giovanni Fiorentini, whose significant contributions to the field of geoneutrino studies have left an indelible mark. Although he passed away in June 2022, his memory continues to live on in our hearts.

## References

[1] Fiorentini G., Lissia M. and Mantovani F., "Geo-neutrinos and earth's interior", *Phys. Rep.*, **453** (2007) 117. DOI: 10.1016/j.physrep.2007.09.001.

[2] Eguchi K. *et al.*, "First results from KamLAND: Evidence for reactor antineutrino disappearance", *Phys. Rev. Lett.*, **90** (2003) 021802.

[3] Araki T. *et al.*, "Experimental investigation of geologically produced antineutrinos with KamLAND", *Nature*, **436** (2005) 499. DOI: 10.1038/nature03980.

[4] Watanabe H., "Geoneutrino measurements with KamLAND", Presentation at the International Workshop: *Neutrino Geoscience* (Prague, 2019) `https://indico.cern.ch/event/825708`.

[5] Alimonti G. *et al.*, "The Borexino detector at the Laboratori Nazionali del Gran Sasso", *Nucl. Instrum. Methods Phys. Res. A*, **600** (2009) 568. DOI: 10.1016/j.nima.2008.11.076.

[6] Agostini M. *et al.*, "Comprehensive measurement of pp-chain solar neutrinos", *Nature*, **562** (2018) 505. DOI: 10.1038/s41586-018-0624-y.

[7] Agostini M. *et al.*, "Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun", *Nature*, **587** (2020) 577. DOI: 10.1038/s41586-020-2934-0.

[8] Bellini G. *et al.*, "Observation of geo-neutrinos", *Phys. Lett. B*, **687** (2010) 299. DOI: 10.1016/j.physletb.2010.03.051.

[9] Agostini M. *et al.*, "Comprehensive geoneutrino analysis with Borexino", *Phys. Rev. D*, **101** (2020) 012009. DOI: 10.1103/PhysRevD.101.012009.

[10] Fiorentini G. *et al.*, "Mantle geoneutrinos in KamLAND and Borexino", *Phys. Rev. D*, **86** (2012) 033004. DOI: 10.1103/PhysRevD.86.033004.

[11] Coltorti M. *et al.*, "U and Th content in the Central Apennines continental crust: A contribution to the determination of the geo-neutrinos flux at LNGS", *Geochim. Cosmochim. Acta*, **75** (2011) 2271. DOI: 10.1016/j.gca.2011.01.024.

[12] Huang Y. *et al.*, "A reference Earth model for the heat-producing elements and associated geoneutrino flux", *Geochem. Geophys. Geosyst.*, **14** (2013) 2023. DOI: 10.1002/ggge.20129.

[13] Bellini G. *et al.*, "Geoneutrinos and geoscience: an intriguing joint-venture", *Riv. Nuovo Cimento*, **45** (2021) 1. DOI: 10.1007/s40766-021-00026-7.

[14] Davies J. H. and Davies D. R., "Earth's surface heat flux", *Solid Earth*, **1** (2010) 5. DOI: 10.5194/se-1-5-2010.

[15] Tam B., "The SNO+ Experiment: Reactor & Solar $\nu$ Prospects", in *Proceedings of Neutrino Oscillation Workshop — PoS(NOW2022)* 2022.

[16] Strati V. *et al.*, "Perceiving the Crust in 3-D: A Model Integrating Geological, Geochemical, and Geophysical Data", *Geochem. Geophys. Geosyst.*, **18** (2017) 4326. DOI: 10.1002/2017gc007067.

[17] "JUNO physics and detector", *Progr. Particle Nucl. Phys.*, **123** (2022) 103927. DOI: 10.1016/j.ppnp.2021.103927.

[18] Beacom J. F. *et al.*, "Physics prospects of the Jinping neutrino experiment", *Chin. Phys. C*, **41** (2017) 023002. DOI: 10.1088/1674-1137/41/2/023002.

[19] Watanabe H. *et al.*, "Ocean Bottom Detector: frontier of technology for understanding the mantle by geoneutrinos", in *2023 IEEE Underwater Technology (UT)* pp. 1-5.

[20] Šrámek O. *et al.*, "Revealing the Earth's mantle from the tallest mountains using the Jinping Neutrino Experiment", *Sci. Rep.*, **6** (2016) 33034. DOI: 10.1038/srep33034.