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Towards a refined reference Earth model for geo-neutrinos

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Abstract. Recently the Borexino [1] and KamLAND [2] collaborations reported evidence of the geo-neutrino signal at more than 4 sigma. These experimental results constrain the contribution of radiogenic heat production in the Earth and provide a crucial test of the existing Bulk Silicate Earth (BSE) models. We developed a high resolution, geospatial reference model for the crust and lithospheric mantle in order to determine the U and Th concentration in the deep Earth from the geo-neutrino signal.

1. Overview of current geo-neutrinos experiments

The KamLAND and Borexino experiments began taking data in December 2002 and March 2007 respectively and are presently the only two operational geo-neutrinos detectors; SNO+ will begin to collect data in 2013.

The Borexino detector contains 278 tons of Liquid Scintillator (LS) confined within a thin spherical nylon vessel with a radius of 4.25 m. The scintillation light is detected by 2212 8" PMT's, which cover nearly 30% of the sphere. In 482 days of live time (December 2007 – December 2009) and in a fiducial mass of 225 tons, the detector collected 21 events with a visible energy below 8 MeV [3]. After a rate-shape-time analysis, the best estimate is $N_B = 9.9^{+4.1}_{-3.4}$ (1σ) geo-neutrinos events, which correspond to $S_B = 64.8^{+26.6}_{-21.6}$ TNU, where 1 TNU (Terrestrial Neutrino Unit) corresponds to one event per 10^{32} target nuclei per year. The null hypothesis for geo-neutrinos is rejected at 4.2σ [1].

The KamLAND experiment uses the largest low energy antineutrino detector ever built, which consists of about 1000 tons of LS contained in a 6.5 m radius spherical vessel viewed by 1879 17" photomultiplier tubes (PMT) that cover 34% of the sphere. During 2135 live-days (March 2002 – November 2009) the detector collected 841 antineutrinos events in the geo-neutrinos energy window in a spherical fiducial volume of radius 6.0 m. After the rate-shape-time analysis the best geo-neutrino estimate is $N_K = 106^{+29}_{-28}$ (1σ) geo-neutrinos events, corresponding to $S_K = 38.3^{+10.3}_{-9.9}$ TNU. The null hypothesis for geo-neutrinos is rejected at the 4σ level [2].

2. Geo-neutrinos and the global properties of the Earth

Determining the geo-neutrino flux from multiple sites is a future research frontier that can provide constraints on the mantle flux, provided that a robust global geochemical and thermal reference frame can be created. Mantovani et al. (2004) [4] provided the first global surface flux model. The recent KamLAND result [2] reported the first direct estimate of the radiogenic heat production of the Earth

($20^{+8.8}_{-8.6}$ TW) and concluded that Earth's primordial heat supply has not yet been exhausted and that radiogenic heat contributes some, but not all, of the total surface heat flux. The expectations of the scientific community are very high; in the next decade, geo-neutrino science has the potential to resolve some important questions that are still debated (e.g., what is the composition of the Bulk Silicate Earth (BSE)? How much U and Th are in the crust and in the mantle? What is the bulk Th/U ratio of the Earth?).

The predicted abundance and distribution of U and Th in the present-day mantle are model dependent: a global description of the present crust-mantle system is, in part, constrained by the assumed BSE model. Such models describe the composition of primordial silicate Earth, subsequent to core separation and prior to crust production and are based on geochemical and cosmochemical arguments. The range of BSE models predict differing absolute abundances of U and Th, which has significant implications for the amount of radiogenic heat production in the mantle and geo-neutrino flux (table 1). Figure 1 shows the potential of KamLAND results for testing the different BSE models. Combining the contributions from crust and mantle we obtain the upper and lower bounds on the geo-neutrino signal as a function of the radiogenic heat production rate H(U+Th). For a fixed total U and Th mass, the highest signal is obtained by assigning to the crust the maximum U and Th content that is consistent with observational data and putting the rest in the mantle with a uniform distribution. Similarly, the minimal signal is obtained for the minimal U and Th mass in the crust and the rest in a thin layer at the bottom of the mantle. Although the 1σ experimental uncertainties of the geo-neutrino signal at KamLAND is still greater than 25%, some BSE models fall outside this limit.

Table 1. Global mass of U, Th/U ratio and radiogenic heat production rate H(U+Th) in the silicate Earth according to different BSE models. The numbers of the first column are reported in figure 1.

	Authors of different BSE models	m(U) [10^{17} kg]	Th/U	H(U+Th) [TW]
1	Javoy et al. (2010) [5]	0.5	3.5	9.2
2	Lyubetskaya and Korenaga (2007) [6]	0.7	3.7	13.4
3	McDonough and Sun (1995) [7]	0.8	3.9	16.2
4	Allegre et al. (1995) [8]	0.8	3.9	16.2
5	Palme and O'Neil (2003) [9]	0.9	3.8	17.6
6	Anderson (2007) [10]	1.1	4.0	23.0
7	Turcotte and Schubert (2002) [11]	1.2	4.0	25.4

The extremes of the band in Figure 1 correspond to the whole range of uncertainty, which includes ±3σ interval for statistical errors and all modern estimates of geochemical and geophysical parameters according to [12]. The width of the band depends on uncertainties concerning the U and Th mass and distribution in the crust and in the region surrounding the detector. In this context, refinement of the geophysical and geochemical crustal model used in estimating the expected geo-neutrino flux is desirable. Importantly, future counting and additional detectors will provide more critical limits on the acceptable range of model compositions.

3. Building a global refined reference model of the Earth

We are developing a refined reference model for the crust and lithospheric mantle by better defining the abundances of Th and U and their 3-dimensional distribution. Given a 1°x1° surface map of the Earth [13] the underlying crust is described as a seven-layer structure, which is characterized using seismic velocities to discriminate layers of sediments, upper, middle and lower crust. Using these physical constraints combined with new compilations of geochemical data for sediments and for oceanic and continental crust, we estimate the expected geo-neutrino signal and its uncertainties for the crust of the Earth. Evaluating the U and Th abundances and their uncertainties in the middle and lower continental crust have been a focus of this model, along with using seismic velocity data to determine the lithological makeup of these layers. The deep portions of the continental crust have been characterized as a mixture of felsic and mafic lithologies whose proportions are estimated by comparing the velocities of longitudinal and transverse seismic waves reported in the crustal model with the laboratory values obtained for ultrasonic velocities of different rock types.

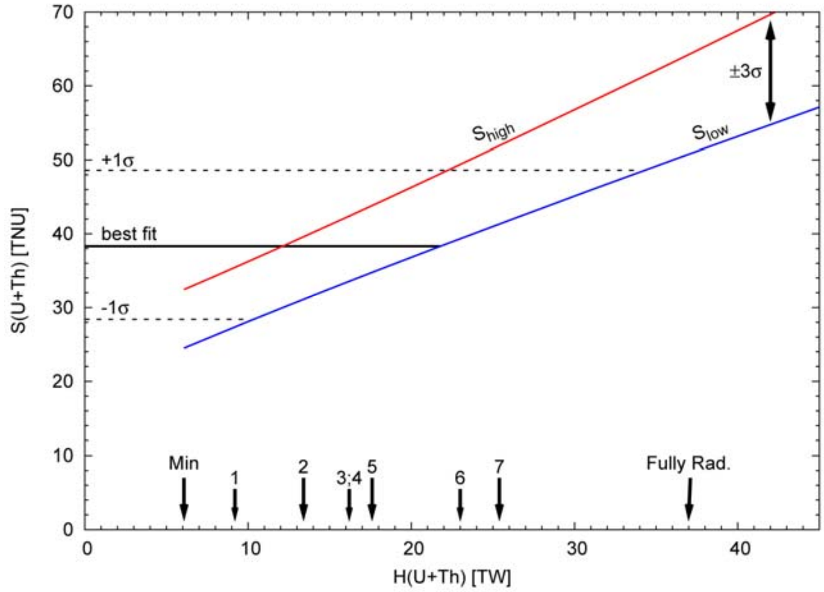

Figure 1. The predicted signal S(U+Th) from uranium and thorium geo-neutrinos at KamLAND as a function of radiogenic heat production rate H(U+Th). The black solid line denotes the best value reported by KamLAND Collaboration [2]; the dotted lines are the 1σ uncertainties of this measurement. The numbers associated to the arrows on the x axis refer to models reported in table 1. See text for more details about S_{high} and S_{low}.

We compiled existing laboratory ultrasonic velocity data for various deep crustal rock types and summarized their average seismic properties at a confining pressure of 0.6 GPa and room temperature. Metamorphosed igneous rocks were subdivided into two groups based on metamorphic facies and/or mineralogy: amphibolite facies and granulite facies, to represent the main rock types in the middle and lower continental crust, respectively. For both felsic and mafic end members of the two groups, the frequency distributions of Vp and Vs are generally Gaussian, which inspire us to use mean values to represent their central values. In the middle continental crust, the felsic end member has an average Vp of 6.34±0.16 km/s and a Vs of 3.65±0.12 km/s, while the mafic end member has an average Vp of 6.98±0.20 km/s and a Vs of 3.93±0.15 km/s. In the lower continental crust, felsic rocks typically have average Vp and Vs of 6.52±0.19 km/s and 3.70±0.11 km/s respectively, while for average Vp and Vs of mafic rocks we obtain 7.21±0.20 km/s and 3.96±0.14 km/s. To compare our compiled laboratory ultrasonic velocities to the velocities of longitudinal and transverse seismic waves reported in the crustal model, we applied pressure and temperature derivatives of $\sim 2 \times 10^{-4}$ km s^{-1} MPa^{-1} and $\sim 4 \times 10^{-4}$ km s^{-1} $^oC^{-1}$, respectively, for both Vp and Vs, and assumed a crustal geothermal gradient of 30°C km^{-1}.

The U and Th abundances for thousands of samples from the middle (amphibolite) and lower (granulite) continental crust were critically compiled and exibit log-normal distributions. Thus, we took the logarithm of their abundances to convert it into normal distributions. Figure 2 shows the dispersion of U and Th abundances in the middle crust (amphibolite facies rocks) and lower crust (granulite facies rocks).

Using the U and Th abundances measured in peridotites, combined with constraints on the conductive geotherm provided by thermobarometry of mantle xenolith suites, we constrained the expected geo-neutrino signal from the lithospheric mantle. The sub-lithospheric mantle is treated as a two-layer shell, with heat-producing element depleted layer overlying an enriched layer.

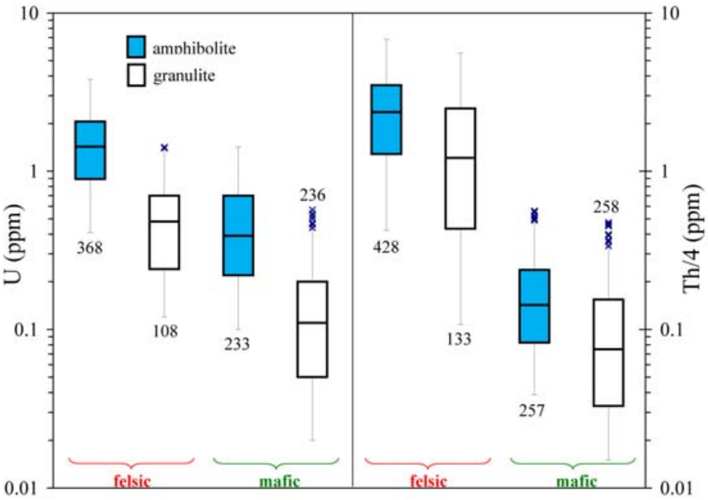

Figure 2. Box-and-whisker diagram showing the U and Th abundances dispersion in the amphibolite and granulite facies rocks. The numbers of samples are shown above or below the whiskers. Any data that are not included within the whiskers are plotted as outliers (crosses). The adopted values are: $a(U)_{Fel}^{Am}$ = 1.4 ppm, $a(Th)_{Fel}^{Am}$ = 8.3 ppm, $a(U)_{Maf}^{Am}$ = 0.4 ppm, $a(Th)_{Mafl}^{Am}$ = 0.6 ppm, $a(U)_{Fel}^{Gr}$ = 0.4 ppm, $a(Th)_{Fel}^{Gr}$ = 3.9 ppm, $a(U)_{Maf}^{Gr}$ = 0.1 ppm, $a(Th)_{Mafl}^{Gr}$ = 0.3 ppm.

4. Conclusion and perspectives

The KamLAND experiment measured for the first time the terrestrial heat power from U and Th. Geo-neutrino data from multiple sites will be the research frontier allowing constraints on the global geochemical properties of the Earth. A refined reference model of the crust for estimating the geo-neutrino signal has been made. The middle and lower crust represent differing mixtures of felsic and mafic rocks with proportions determined from seismic observations. Geochemical data for amphibolites (middle crust) and granulites (lower crust) allow assignment of Th and U abundances to these regions of the crust; producing a crust with a heterogeneous vertical distribution of U and Th. The obtained total mass of U and Th in the crust is 2.6×10^{16} kg and 11.3×10^{16} kg respectively, which corresponds to a U and Th radiogenic heat productions of 2.6 TW and 3.0 TW, respectively. This crustal power can be compared with 6.0 TW obtained using the U and Th abundances of the bulk continental crust reported in [14]. The un-oscillated geo-neutrino flux from U and Th in crust drops by about 20% respect that calculated in [4]. The lithospheric mantle is estimated to have an un-oscillated geo-neutrino flux of some 10^4 cm^{-2} s^{-1} produced by 0.4×10^{16} kg of U and 1.7×10^{16} kg of Th. Future improvements of this refined reference model will combine uncertainties from crustal structure, distribution of U and Th measurements and seismic data and use global surface heat flow to constrain crustal geotherms in making temperature corrections.

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