The Promises of Geoneutrinos

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Abstract. Neutrinos have been studied ever since they were predicted by Pauli with ever increasing vigor. The recent flurry of studies on neutrinos from the Earth is coming from its first detection in 2003 at Kamiokande which has already set some non trivial limits on the radiogenic heat flux. Geoneutrino detection in future experiments hold the promises of both improving our knowledge of neutrino's properties as well as of the geophysics of the Earth. It may even settle definitively the controversial issue of whether or not there could be a georeactor at the centre of our planet

1. The messengers of astronomy
Modern astronomy has opened up various windows to look at the Universe. The electromagnetic window has been for a long time confined to the optical part of the spectrum accessible through the use of reflecting telescopes. The invention of the radar led to the birth of radio-astronomy after WWII opening up the radio window. Then space age allowed us to place our telescopes beyond the atmosphere and thus free from atmospheric absorption and turbulence, opening up the infrared, ultraviolet, X rays and then gamma rays branches of astronomy. But astronomy, namely the study of the Universe, needs not stop at electromagnetic astronomy. Indeed other particle messengers beside the photon can be detected on Earth and inform us on the properties of matter whether stellar, galactic or even extragalactic. There is first cosmic ray astronomy where the messenger is mostly the proton. Being stable, the proton can propagate through huge distances but being a charged particle we lose directional information about the source save for ultra high protons beyond $10^{18}$eV. Graviton astronomy attempts to start with gravitational waves interferometers like LIGO and VIRGO. The idea is to detect the gravitational waves either primordial or coming from the asymmetric merging of massive compact objects like neutron stars or black holes.

2. Neutrino astronomy
Neutrino astronomy is a somewhat late comer in multi-messenger astronomy. It all started with the detection of a handful of neutrinos in 1987 when SN 1987A situated in the Large Magellanic Cloud galaxy next to our Milky Way exploded thus releasing most of its energy in neutrino form, some of which reached Earth on that fateful day of 23 February 1987. Solar neutrino astronomy started few years earlier when it was found a deficit on the number of solar neutrinos received in underground detectors. In addition, atmospheric neutrinos detection (Superkamiokande and Borexino detectors notably) coming from the decay of muons generated in cosmic rays air showers started in earnest. All this along with the various ongoing long baseline experiments has enabled us to determine most of the neutrino mixing matrix parameters. The first galactic neutrinos were detected in 2013 by the billion
ton detector Ice Cube which is tracking neutrinos coming from below ground (and thus coming from the Northern hemisphere sky). At term, it should measure their flux and identify some of their sources which presumably are Active Galactic Nuclei (AGN) as well as Gamma-ray bursts and starburst galaxies. We can see displayed in Fig 1 the various neutrinos sources spanning a very large energy spectrum.

![Neutrino fluxes from the various astrophysical and terrestrial sources.](image)

**Figure 1.** Neutrino fluxes from the various astrophysical and terrestrial sources.

In addition to all these astrophysical neutrino sources, there exists a neutrino cosmic background at slightly lower temperature and density than the photon CMB produced some 13.7 billion years ago a little bit prior to the matter photons decoupling. Due to their extremely low energy, there is no foreseeable experiment which could detect them. Although they are only the second most abundant particles in the Universe after the photon, yet due their non-zero mass, they most likely give the largest contribution to the mass of ordinary matter.

Neutrino astronomy may also indirectly detect dark matter as dark matter candidates involves in many scenarios the weak interaction and thus very high energy neutrino pairs would be produced.

### 3. Geoneutrinos

Detecting geoneutrinos, that is neutrinos produced in the Earth interior from the decay of radioactive nuclides has become a reality in the past decade. The birth of what can be called neutrino geophysics took place at first with the KamLAND detector in Japan in 2005 when a non zero anti-neutrino signal was laboriously separated from the nuclear reactors background. It was then confirmed and consolidated at the Borexino detector at the Gran Sasso facility in Italy in 2010. Since then, more detections took place at those facilities, and several other dedicated ones are about to enter the fray. The idea of detecting geoneutrinos was put forward in the early sixties by Eden [1], Marx [2] and Markov [3], and argued further about its possibility in the eighties notably by Krauss, Schramm and Glashow [4].
The basic idea which makes this new tool for geophysics so exciting is its ability to determine quantitatively the geothermal heat that flows from the Earth occurring from radioactive elements like $^{235}$U, $^{232}$Th and $^{40}$K. An average value of this internal heat is 60mW/m$^2$ which gives an overall value of 30-44 TW for the whole Earth. Indeed, a crucial issue facing geophysics is that unlike the density profile of the Earth which is rather well known from seismologic data, the elemental composition is not known save from geophysical arguments and hints from composition from chondritic meteorites as we have not been able to probe directly the Earth interior beyond a 12km depth. The Bulk Silicate Earth [5] model (BSE) has been built describing the primitive mantle, that is after core separation, and which notably predicts the global distribution of the radiogenic elements. Although compatible with most observations, it has been gotten by a chain of arguments and can’t be taken with total confidence. Furthermore it has to be in practise supplemented with estimates from the fractions of Uranium in the crust and in continental mass as this play a crucial role in evaluating the expected antineutrinos rates at the specific detector location.

![Figure 2 and 3. At left, the map of the Earth’s total surface heat flow. The flux ranges from low values (~10mw/m$^2$) at some oceanic spots to much higher values (~300mW/m$^2$) at hot spots at the dorsal with an overall average value of some 60mW/m$^2$. At right, the distribution of nuclear reactors on Earth. We see that the antineutrinos from those facilities could be reduced dramatically if we choose adequately the location of our detector. Furthermore, it has little to say about the possible existence of Uranium in the Earth core as it has been speculated by some dissident geophysicists. Arguments are based on the lithophile character of Uranium and Thorium which, according to the BSE model, prefer despite their high density, to be in the silicate or the molten rocks surrounding the core rather than in the core itself made of iron and other metals having some chemical affinity with it. Additionally, the Urey’s ratio which measures the total energy radiated by Earth with respect to the radiogenic heat and which is currently estimated to be 0.5 to 0.6, strongly suggests that the radiogenic energy is the dominant source of the Earth energy outflow without being the only one, although a rate of 1 is not excluded. Now a beautiful way to probe the issue of the Earth energy source is to detect anti neutrinos from the decay of the Uranium and Thorium nuclides as they are directly related to the radiogenic heat. Let us recall, to underscore the importance of the issue, that the Earth internal heat flow is a crucial parameter to understand Earth as it drives every process inside it, most notably plate tectonic, volcanoes, the Earth magnetic field and the like. Since the antineutrinos are coming from the natural beta decay of the radiogenic nuclides, it comes mainly through the three chains:
where $T_{1/2}$ is the half-life, $E_{\text{max}}$ is the antineutrino maximal energy, $Q$ is the Q-ratio of the reaction, while $\varepsilon_\nu$ and $\varepsilon_H$ are respectively the $\bar{\nu}_e$ luminosity and the heat production rate per unit mass.

Now the last reaction produces antineutrinos with too low energy and which can't be detected by the inverse beta decay on free protons as this later reaction is endothermic with threshold at 1.81 MeV $\bar{\nu}_e + p \rightarrow e^- + n$ and so its rate can only be inferred. From there, we can readily compute the radiogenic luminosity and deduce from it the heat production once we are provided with the global abundances of those elements.

| Decay                  | $T_{1/2}$ | $E_{\text{max}}$ | $Q$   | $\varepsilon_\nu$ | $\varepsilon_H$ |
|------------------------|-----------|------------------|-------|-------------------|-----------------|
| $^{238}\text{U} \rightarrow ^{206}\text{Pb} + 8\ ^4\text{He} + 6e + 6\bar{\nu}$ | 4.47      | 3.26             | 51.7  | $7.46 \times 10^7$ | 0.95 $\times 10^{-4}$|
| $^{232}\text{Th} \rightarrow ^{208}\text{Pb} + 6\ ^4\text{He} + 4e + 4\bar{\nu}$ | 14.0      | 2.25             | 42.7  | $1.62 \times 10^7$ | 0.27 $\times 10^{-4}$|
| $^{40}\text{K} \rightarrow ^{40}\text{Ca} + e + \bar{\nu}$ (89%)        | 1.28      | 1.311            | 1.311 | $2.32 \times 10^8$ | 0.22 $\times 10^{-4}$|

**Figure 4.** The energy output from the main radiogenic reactions

Adopting a specific mass distribution model (Like the BSE), we can find the differential luminosity for geoneutrinos which enables us to make predictions on the radiogenic energy output based on the signal at each detector. Luckily, solar neutrinos do not constitute a background since the reaction above is not occurring. The real background is from the some 450 nuclear reactors disseminated over much of the lands and which make the detector's location a crucial factor in the analysis as the geoneutrinos count will be deduced after subtracting out those reactors antineutrinos from the overall detection rates.

The results using the BSE model is summarized in this table [7].

**Figure 5.** Geoneutrino luminosity for each radiogenic series (from Enomoto's site [6]).
The computed luminosity $L_{\nu}$ and heat $H_R$ generated by the main three reaction contributing to the radiogenic energy output with the geophysical estimated overall mass content values of those elements.

Thus the total radiogenic heat is the sum of the three contributions and give 18.4TW, which constitutes a substantial fraction of the total internal Earth outflow. Notice that according to the BSE paradigm, no contribution has been assumed from the core since it is supposed to be Uranium and Thorium depleted. Since all of the estimates, whether the overall energy outflow or the radiogenic heat, are uncertain by a factor of possibly two, the ranges of the various estimates in the literature for the radiogenic heat being between 19TW to 31TW, while the overall Earth output ranges between 30TW to 44TW, thus uncertain by a factor of possibly two. It is clear that the question of the origin of Earth heat is not settled. Yet the necessity of including the radiogenic output is strong while at the same time the other energy sources which might have been important in the past like gravitational energy release during chemical differentiation, the tidal fiction, meteoritic impact are majored.

This leaves some place for other models, called sometimes "heretical" geophysical models, which ranges from challenging the standard BSE abundances or the cosmochemical estimates on which it is partially based (The CI chondrites might not be the original material from which the Earth was formed), to more severe modifications like assuming that a large amount of Potassium might be locked inside the Earth's core [8], thus driving up the Earth's energy budget. An even more revolutionary modification to the standard BSE model is the core geo-reactor hypothesis by Herndon [9] whereby a large amount of Uranium at the Earth centre would have formed a breeder reactor. Unambiguous determination of the radiogenic heat production will be needed before neutrino geophysics could say to have contributed decisively to geophysical issues.

### Figure 6

|         | $m$ [10$^{17}$ kg] | $H_R$ [10$^{12}$ W] | $L_{\nu}$ [10$^{24}$ s$^{-1}$] |
|---------|--------------------|---------------------|-------------------------------|
| U       | 0.8                | 7.6                 | 5.9                           |
| Th      | 3.1                | 8.5                 | 5.0                           |
| $^{40}$K| 0.8                | 3.3                 | 21.6                          |

4. The geoneutrinos detectors

The first detector to have caught low energy geoneutrinos was KamLAND (Kamioka Liquid Scintillator Antineutrino Detector) located at the Kamioka Observatory in Japan, thus heralding the birth of neutrinos geophysics. It consists of a 1000t scintillator detector surrounded by 1845 PMTs and located at some 1000m underground to avoid the cosmic ray background. Yet the nuclear reactors background is formidable and has to be extracted from the detected events to isolate the signal.
Figure 7. At left is the KamLAND at the Kamioka Observatory deep underground. At right is the Borexino detector in the Gran Sasso tunnel.

The first announcement in July 2005 resulted from the analysis of 749 days of data: From the 152 detected $\nu_e$, a central value of 28 could be attributed to geoneutrinos, giving a 60TW upper limit on the Earth radiogenic output. Furthermore, it excludes the zero geo-neutrino assumption at almost 2σ. An update of the detector in 2011 brought an additional 106 identified geoneutrinos out of the 841 candidates events improving much the radiogenic output to 20.0 ($+8.8/-8.6$) TW.

Borexino is the second geoneutrinos detector in use. It consists of a real time 0.3 kiloton scintillator calorimeter originally used to detect the $^7$Be from the Sun, and is situated as some 1500 m underground at the Laboratori Nazionali del Gran Sasso in Italy. After a first run in 2011 which first demonstrated the capability of geoneutrino detection with a 3σ signal, a second run (1352 days) in 2013 identified 14 geoneutrinos out of 46 detected, the remaining ones being accounted for by the nuclear reactors and only one of them from the detector tank thanks to the great radio purity of the liquid scintillator. It thus beneficed with respect to KamLAND from a much lesser nuclear reactor background. The data seems to reject the Earth's core georeactor hypothesis, limiting in any case its power to no more than 3 TW (95% confidence level).

5. The Georeactor in the Earth's Core hypothesis

This radical hypothesis proposed by M. Herndon is certainly not the geophysicist's paradigm as it assumes the existence of a natural nuclear reactor with power up to 10 TW operating in the center of the Earth. Yet, as argued before and although it is not mainstream theory, it can't be ruled out by any experiment yet. A case for its plausibility can be made from the occurrence of natural reactors like the Oklo one in Gabon which has undergone in the past a spontaneous ignition of uranium in mineral deposits some 1.7 billion years ago. If the geo-reactor exists, its anti-neutrino will contribute to the radiogenic outflow. Now with KamLAND and Borexino data, we have for the first time better constraints on its existence, namely an upper limit on the power of the geo-reactor although it is not strong enough to exclude the hypothesis altogether. The best fit is:

$$H_0 = 5.9^{+6.4}_{-5.9} \text{TW}$$

As for the upper limit on the geo-reactor power, it is 19 TW at 90% C.L with some dependency from the choice of the oscillation parameters. Ideally, a way which could determine the geoneutrino's angular distribution [10] could help settle the issue as we could in particular discriminate the antineutrinos coming from the core from those coming from the mantle. It could also discriminate those from nuclear reactors and the crust coming close to
horizontal from those from the mantle reaching the detector with a pronounced dip angle. That would imply other detection techniques as the one used till now and based on inverse beta decay on protons which is not directional [11].

Let us call \( I(\theta, \phi) \) the intensity of geoneutrinos at the Earth surface, so that \( F \) the flux distribution of neutrinos would be, following Fields, Brian D. et al:

\[
I(\theta, \phi) = \frac{dF}{d\Omega}
\]

Dividing the Earth in concentric spherical layers, we can compute the differential neutrino flux at the surface or close enough to it according to various hypothesis on the distribution of the radiogenic elements according to the depth.

Now assuming various global abundances for the uranium in the core, we can see the great discriminating power that could provide us a directional capability at the detector.

Figure 8 and 9: The differential neutrino flux at the Earth surface under various assumptions in function of the nadir angle, with an angle \( \theta = 0 \) corresponding to the direction of the Earth center and \( \theta = 90 \) corresponding to the horizontal direction.

In the diagram at lower left, we see the effect on the angular antineutrino flux for the various radiogenic elements according to the BSE model. At upper left, we see the influence on the flux of several uniform elemental distributions, within the whole Earth, within the crust only and finally within the core only. The diagrams at right give the angular flux under the hypothesis of various global abundances for the potassium if situated in the core.

6. The future detectors

Quite few detectors are planned to study further the geoneutrinos. We will focus on two of them,
- SNO+ which is about to take data, and the other one Hanohano quite revolutionary by all standards and which is in an advanced stage of planning. Two others also with great potential for geophysics will be briefly mentioned at the end of the section.

- The SNO+ (Sudbury Neutrino Observatory+) detector at SNOLAB near Sudbury in Canada is filled with 780 tons of liquid scintillator in a 12 m diameter acrylic sphere shielded by some ultra pure water along with 9000 photomultipliers. geology is extremely well studied. The antineutrino signal will be dominated at about the 80% level by the crustal component. It should provide data on the composition of the continents as well as place limits on the various models of the composition of the continental crust.

- The Hanohano deep-ocean transportable detector
It is a proposed mobile sinkable 10 kton liquid scintillator detector to be carried by a ship and deployed in the deep ocean at some 3 to 5 km depth aiming at measuring geo-neutrinos in a quite innovative way.

![Figure 10: The large seafaring vessel constituting the Hanohano project has its detector sinkable making it mobile and highly versatile. The challenges facing I are both technological and logistic.](image)

It is to be positioned at the oceanic crust near Hawaii since the oceanic crust is thin and assumedly depleted in U and Th with respect to continental crust which will furthermore reduce background from nuclear power reactors. Yet being portable it should be paced at various oceanic locations and be lowered there. Its expected detection rate is about 100 geo-neutrinos per year (For only around 12 reactor antineutrinos per year), and it should be able to also measure the Th/U ratio of the mantle at the 10% precision level in addition to potentially determine the neutrino mass hierarchy.

- The Daya Bay 2 experiment [12] in China is characterized by a very large mass of some 20 kton and is supposed to detect up to 400 geo-neutrinos per year. Unfortunately, being very close from a reactor, the $\bar{\nu}_\tau$ background is huge. In the mean time, the facility made the news in 2012 when an antineutrino disappearance experiment improved much on the value of the $\theta_{13}$ mixing angle, finding it yet surprisingly larger than expected.
The expected geoneutrino flux from the various Earth layers in function of the distance to the detector.
- The LENA (Low Energy Neutrino Astronomy) detector scientific consists of a huge 50 kton liquid scintillator multidisciplinary neutrino detector for which geoneutrinos measurement is one of its main scientific goals [12]. It has the potential of detecting some 1000 geoneutrinos per year. The diagram below shows the running and planned experiments.

Figure 11: The expected geoneutrino flux from the various Earth layers in function of the distance to the detector.

Figure 12. The running and planned experiments for geoneutrinos with indication on the Earth layers probed according to their location.
7. Conclusion
Geoneutrinos have the potential to provide us with information on the Earth interior unavailable by other means and test in a unique way the standard model of geophysics. Most notably, it should enable us to settle the long standing controversy on the source of Earth's heat, whether geophysics or radiogenic, the ratio of U/Th, and their respective amount in the crust and the mantle, and even the core if any. And although it started as an offshoot of the new field of neutrino astrophysics it has acquired a life on its own. The coming to age of multi kilotons detectors promises to usher neutrino geophysics into a golden age.

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