Quest for a Nuclear Georeactor

Introduction

In a time when astronauts orbit the Earth and visit the Moon, and mankind has brought vehicles to Mars and telescopes into orbit, we seldom realise that we have penetrated the Earth by only 12 km, a distance smaller than we commute daily to our work or equivalent to the cruising altitude of airplanes. Consequently, we know little about the interior of our planet, except from seismic information and study of the composition of meteorites. Recently our knowledge about antineutrinos has reached the stage that they can be used as a tool, allowing us to look at radiogenic heat sources in the interior part of the planet and associated processes.

The current understanding of the interior of our planet starts from seismological investigations by Oldham (1906) and Gutenberg (1914) that leads to the hypothesis that up to half the radius of the Earth is occupied by a fluid core. From the interpretations of earthquakes, Lehmann (1936) recognised a small, solid inner core. The fact that meteorites consist of nickelferrous iron, lead to the assumption that the fluid core of the Earth consists of molten nickel-iron. Density information stems from the work of Birch (1952). He hypothesised from seismological models and knowledge on high-pressure equations of state that the outer core was composed of a liquid iron alloy and an inner solid core of crystalline iron. The melting temperature of the alloy at the respective pressure defines the boundary. Estimates for this temperature at a pressure of 330 GPa range between 5000 and 6000 K. Figure 1 presents the principal divisions and physical states of the Earth's interior. The absence of shear velocity V_s of earthquake waves is the basis for a fluid core. The density curve shows, in addition to the major changes at the principal sections, steps in the upper mantle at about 420 km and 660 km depth.

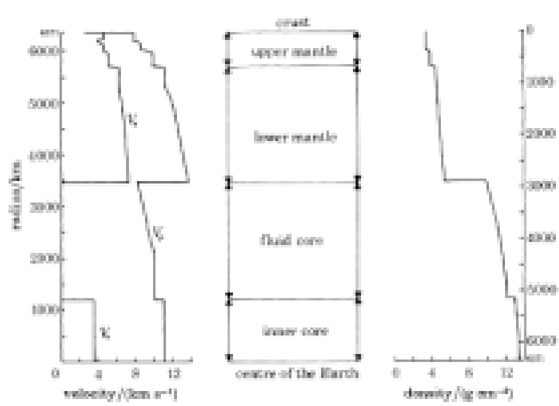

Figure 1. *Schematic representation of the principal partitions and physical states of the Earth's interior. The compressional and shear velocities of earthquake waves, presented in the right panel, are indicated by V_p and V_s, respectively. In the right panel the density as function of depth is presented. (Figure taken from Herndon, 1980).*

Heat loss from the core depends on the radial temperature gradient at the boundary of core and overlying mantle and is strongly related to mantle dynamics. There exists a large uncertainty in ΔT, due to the temperature at the inner-core boundary: ΔT= 1000 to 1800 K (Anderson 2002) over a layer of a few hundred kilometres (Lay et al. 1998). Including the thermal conductivity of the mantle silicates yields a heat flux of 0.04–0.08 W/m^2, leading to a total heat flow from the core of 6–12TW (Buffett, 2003); a considerable part of the estimated total heat flow from the Earth of 40–50TW. The total heat flow at the core-mantle boundary raises vital questions on the thermal evolution of the core and its heat sources in relation to power required to maintain the magnetic field. Radiogenic elements like ^{40}K are thought to play an essential role (Rama Murthy et al. 2003).

Buffett (2003) concludes that "the thermal state of the core remains unclear and that better knowledge of the partitioning of all radiogenic elements between various reservoirs in the planet will help to reduce some ambiguity."

Another ambiguity exists in the chemical composition of the various compartments or reservoirs and especially in the core. In general, one assumes that there is a liquid Fe-Ni alloy core surrounded by a lower and upper mantle and covered by a crust. The bulk composition of the Earth is usually assumed to be the same as that of chondritic meteorites. Within this assumption subsequent hypotheses are made to account for observations at the

Earth's surface.

An intriguing issue is the presence of helium in our atmosphere and in particular its isotope ^{3}He. Whereas ^{4}He is continuously produced by alpha decay, the only way to obtain ^{3}He is either as a primordial relict (e.g. Seta et al. 2001) or by decay of tritium. For the primordial relict the assumption has to be made that the mantle contains a degassed and a, deeper lying, less-degassed reservoir. The former one shows up at the mid-ocean ridge basalts, the latter one in mantle-plumes basalts. Mantle plumes with extreme high ^{3}He/^{4}He ratios are found at some oceanic islands such as Iceland, Hawaii, Samoa and Galapagos (Kurtz and Geist 1999). One assumption commonly made in interpreting noble gas data from mantle plumes is that the source of mantle plumes is relatively non-degassed lower mantle material. Under this assumption, high ^{3}He/^{4}He ratios indicate plume-like upwelling, since the deep Earth is believed to be a source of primordial ^{3}He with a relatively low time-integrated (U+Th)/He ratio (Georgen et al. 2003). At oceanic islands not only high ^{3}He/^{4}He ratios are found but also normal mid-oceanic island values. This is explained by assuming mixed reservoirs (Stuart et al. 2003).

Recently, Bercovici and Karato (2003) proposed a filtering of the mantle at the 410 km discontinuity of the density (see Figure 1). They propose that the ascending mantle rises out of a transition zone, between the 410 and 600 km discontinuities, into the upper mantle above 410 km. The material undergoes dehydration-induced partial melting that filters out incompatible elements, including He and other noble gases. They propose that this filter model can explain geochemical observations without the need for isolated mantle reservoirs. This model could bridge the gap between geochemists supporting a two-layer model at a boundary of 660 km and seismologists, supporting a whole-mantle model of circulation (Hofmann 2003).

Recently, a possible explanation for some of these questions was proposed by hypothesising a 8 km diameter, nuclear georeactor at the centre of the Earth. The hypothesis for such a reactor originates from the work of Herndon (1992) in applying Fermi's nuclear reactor theory to demonstrate the feasibility of planetary scale nuclear fission reactors. Calculations at Oak Ridge National Laboratory (Hollenbach and Herndon 2001) show that a planetary-scale nuclear reactor can operate over the lifetime of the Earth as a breeder reactor and can produce by ternary fission substantial tritium (decaying to ^{3}He) to explain the high ^{3}He/^{4}He ratios observed in oceanic basalts and fumes of volcanoes at Iceland and Hawaii. Seifritz (2003) shows that the operation of such a breeder reactor is consistent with our knowledge on breeder reactors and corresponds to a stable state.

The possibility of a nuclear georeactor is linked to the state of oxidation in the deep interior of the Earth. Herndon has convincing arguments for a state of oxidation like an enstatite chondrite, different from the more oxidised, ordinary chondrites considered by Birch. As a consequence of the highly reduced state some so-called lithophile elements including Si, Mg, Ca, U, and possibly Th occur in part of the core. These elements, tending to be incompatible in an iron alloy, are expected to precipitate at relative high temperatures. Due to their density, MgS and CaS will float to the core-mantle boundary, whereas uranium sulphide (US) and nickel silicide will sink to the Earth's centre.

At pressures that prevail in the core, U and Th, being high-temperature precipitates and the densest substances, would tend to concentrate in the Earth core by the action of gravity. In that process it will ultimately form a fissionable, critical mass. Fission produces less (half) dense fission products that tend to separate from the more dense actinides. In this way a critical reactor condition can maintain.

According to Herdon (1993) and Hollenbach and Herndon (2001), the frequent but irregular variability in intensity and direction of the Earth's magnetic field may be understandable from such a fission reactor. The production of fission products counteracts the operation of the reactor and if the rate of production exceeds the rate of removal by gravitational diffusion, the output of the reactor will decrease and may even shut down, leading to a diminished and ultimate disappearence of the Earth's magnetic field. As fission products diffuse out of the reactor region and actinides diffuse inwards, the reactor restarts and the geomagnetic field re-establishes itself, either in the same or in the reverse direction. The coupling between the georeactor and the geomagnetic field cannot be direct (Hoyng 2003) and has to proceed through changing heat-flow patterns in the core and ultimately in the mantle.

Although the georeactor hypothesis seems to be able to explain, in principle, phenomena such as elevated ^{3}He/^{4}He ratios and reversal of the geomagnetic field, some questions also remain about the specific mechanisms involved. It is assumed that in the working of the georeactor the fission products are separated from the fuel by diffusion or by buoyancy effects. For both processes it still has to be shown if they are effective enough. First estimates for diffusion, based on an extrapolation (using Arrhenius law) to core temperatures of diffusion coefficients and activation energies for helium in apatite (Dunai, 2000), indicate that transport over a distance of 1 km in a solid metal inner core will take 1 Ma. This is probably an order of magnitude too slow to explain geomagnetic reversals on average every 200,000 years by fission products drifting outwards and so cleaning up the core for a reactor restart. To estimate transport velocities due to buoyancy, detailed calculations are needed, but these velocities are expected to be insignificant because of the micro-gravity conditions in the inner part of the core (Seifritz 2003).

It is also difficult to imagine a sufficiently large outward flux of ^{3}He (needed to explain elevated ^{3}He/^{4}He ratios) produced inside the georeactor because an intact solid inner core will form an almost impenetrable barrier for transport. Moreover, the heat produced by the georeactor has to be removed through the solid inner core and normal heat conductivities for solids are not large enough to prevent the reactor from heating up to very high temperatures.

These estimates are based on extrapolating transport coefficients at ambient conditions to the high temperatures and pressures inside the core and assume a uniform metallic core being one solid piece. A more granular structure of the inner core with a structure of pores or fissures will allow a larger and faster transport of gaseous substances and heat. In such a case it is hard to imagine that the core will be uniform and preferential pathways may exist, which act as chimneys and may cause a non-uniform heating of the inner-outer core boundary.

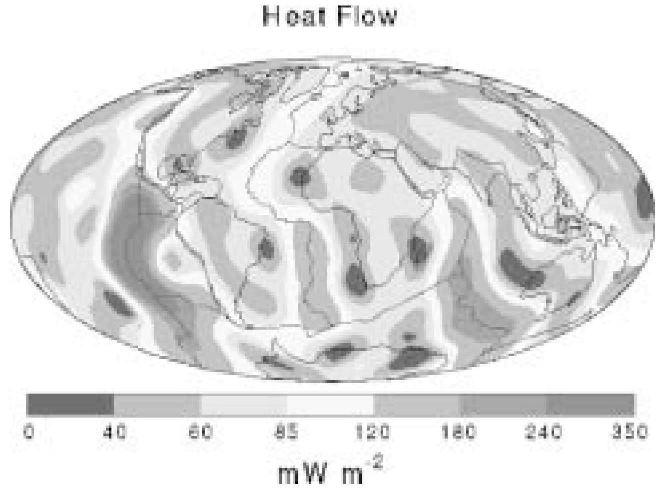

Figure 2. *Map of the heat flow at the Earth's surface. Based on the data of Pollack et al. 1993, and taken from http://www.geo.lsa.umich.edu/IHFC/heatflow.html.*

Antineutrinos as a Tool to Probe the Earth's Interior

The distribution of U and Th in the core and the mantle is not the only question to be answered. Because of the work of Herndon, it is still necessary to find out whether their concentrations decline along their decay series or by fission. One of the few methods to investigate the distribution of natural radionuclides in various reservoirs of the Earth and/or the existence of a nuclear georeactor are antineutrinos produced in β-decay and/or fission, respectively. Fortunately the decay and fission can be distinguished by the energy of the antineutrinos; 2–3 MeV for decay and up to 10 MeV for fission.

As also pointed out by Mantovani et al. (2003), the distribution of Th and U in both the oceanic and continental crust is relatively well known, some information is available on the concentrations of these radionuclides in the upper mantle, but their distribution in the deeper parts of the Earth are unknown. In general for the lower mantel it is assumed that the distribution is homogeneous and spherical symmetric. The fact that surface layers of the Earth have moved significantly throughout geological time is believed to be a surface expression of deeper motions within the Earth. If the heat sources would be homogeneously distributed there would be hardly a reason for these motions. As shown in Figure 2 the heat flow at the Earth surface ranges over an order of magnitude.

Already in 1983 Sheridan made a comparison between a number of features at the Earth surface such as spreading rate of the continents, sea-level stand and calcium-carbonate deposit rates (CCD) and the stability of the magnetic field (see Figure 3). He finds higher spreading rates, higher sea level stands and larger CCD rates at times that the magnetic field is quiet, and relates these phenomena to changes in the circulation patterns in the core and the mantle and the occurrences of mantle plumes at the Earth's surface. Changes in the circulation pattern in the mantle may influence the heat flow at

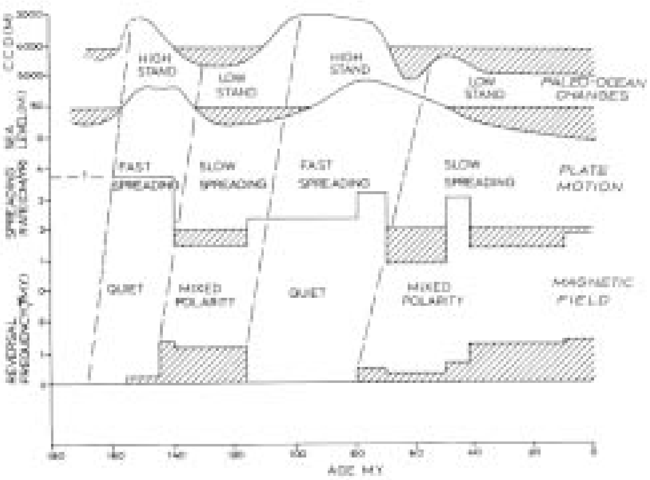

Figure 3. *Correlation over time between magnetic activity, ocean spreading rates, sea-level stands an calcium-carbonate depositon (CCD). This figure is taken from Sheridan, 1983.*

the ocean floors and thereby have an influence on global climate.

All these pieces of information require a better insight of the radiogenic heat sources in the deeper parts of the mantle and especially their inhomogeneities and their deviation from a spherical distribution. The strength of the antineutrino-flux signal at various sites on Earth will therefore be an indication of the distribution of these radionuclides in the compartments of the Earth. According to calculations by Raghavan *et al.* (1998) 40% of the signal will come from sources in the crust within about 450 km, 70% from within 1200 km and 90% from about 6000 km. The sensitivity of the measurements for antineutrino from parts of the mantle and a possible georeactor will therefore be influenced by the location of the detector relative to other (known) sources of antineutrinos such as those coming from the radionuclides in the crust or power reactors. Consequently the project requires directional sensitivity in antineutrino detection and a location that favours the detection of antineutrino sources in the mantle and in the core.

The science and technology of detecting antineutrinos, $\bar{\nu}_e$, are well established. Recently the KamLAND collaboration has confirmed the oscillation phenomena in antineutrinos (Eguchi, 2003) as observed in solar neutrinos. Also the oscillation parameters based on solar neutrinos and fission reactor antineutrinos seem to be established (see Mantovani et al. 2003). In many experiments, we propose to use the detection reaction based on inverse β-decay: $\bar{\nu}_e + p \rightarrow e^+ + n$. The visible energy of the positron signal directly provides the $\bar{\nu}_e$ energy, (E(MeV) = E($\bar{\nu}_e$) – 1.8 + 1.022 = E($\bar{\nu}_e$)–0.78. The signal can be tagged by the signal produced after several microseconds by the thermalised neutron captured by hydrogen in the aromatic organic liquid scintillator. The delayed coincidences suppress the background and the chance coincidence rate in a kiloton scintillator mass detector (such as installed at Kamioka, Japan) can be limited to several events/year (Rhagavan 2002). This corresponds to a sensitivity limit of an antineutrino flux $\Phi(\bar{\nu}_e)_{min}$~10^4 cm^{-2} s^{-1}.

In β-decay, members of the decay series of U and Th antineutrinos, $\bar{\nu}_e$, are produced. The antineutrinos from the geo-reactor will be identical in energy spectrum as those produced in power reactors. In the U series the β-decay of ^{234m}Pa, ^{214}Bi with Q-values of 2.29 and 3.26MeV, respectively, and ^{228}Ac, ^{212}Bi, and ^{208}Tl with Q = 2.11, 2.25 and 1.8 MeV, respectively, can contribute. Geo U/Th signals cut off at E_{e+} of about 2.5MeV.

For reactors—either power reactors or a geo-reactor—the antineutrino spectrum follows from their mean fuel composition, the numbers of antineutrinos per fission event, and their spectrum (see Achkar et al. 1996 and references therein). For these neutrinos, the flux depends on the distance between power reactor and detector. The existing underground laboratories at Gran Sasso, Italy, and Kamioka, Japan, are both situated on the crust and in Kamioka, near power stations.

A 3 to 10TW georeactor would yield at any point near the surface a flux $\Phi(\bar{\nu}_e)_{geo}$~1-3·10^5 cm^{-2} s^{-1} and is an order of magnitude larger than the estimated detector background of ~10^4 cm^{-2} s^{-1}. The detection of antineutrinos from the core is a valid proposition provided the background is sufficiently low. A georeactor is spectrally indistinguishable from power reactors, but the georeactor provides a strongly directional signal. Model calculations indicate that such measurements are feasible in an underground laboratory, provided the background due to the geological formation and antineutrinos produced in nuclear power reactors is sufficiently low. This condition hampers observation in the existing underground

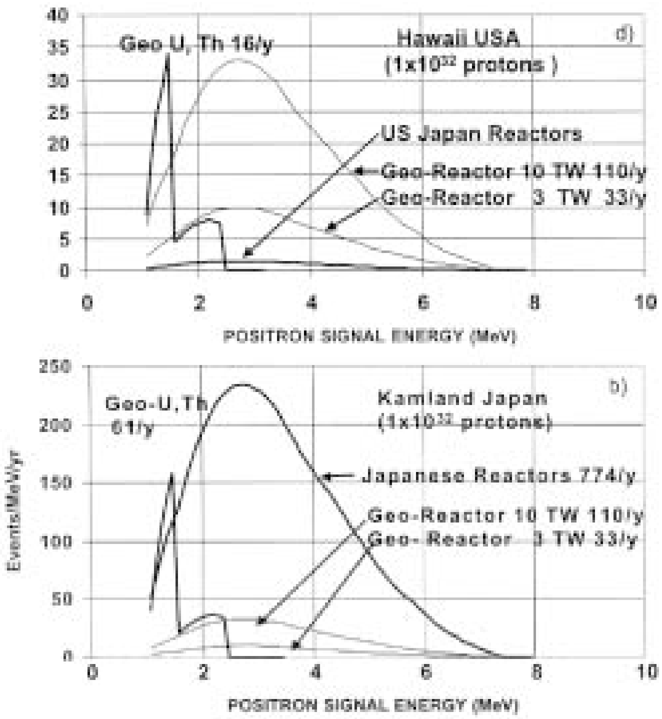

Figure 4. *Calculated positron energy spectrum for two locations: Hawaii and Kamioka. The two locations differ quite strongly in the flux from U/Th antineutrinos and from the antineutrinos produced in nuclear power stations. The situation of Hawaii will be quite similar to the one expected at Curaçao. (Figure taken from Raghavan, 2002.)*

laboratories such as Borexino at Gran Sasso, Italy, and Kamland at Kamioka, Japan, and favours locations such as Hawaii, the Aleuts, and the Antilles. Figure 4 shows the positron energy spectrum for Hawaii and Kamioka (taken from Raghavan 2002). It shows that the background at Kamioka is too large for proper detection. This is recently confirmed by measurements with the Kamland detector yielding 9 ± 6 geo-antineutrinos from an exposure of $1.4 \cdot 10^{31}$ protons year (Fiorentini et al. 2003).

Directional information could be extracted from the recoiling neutron in the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$, for which the recoil angle is on average, $<\Phi_{recoil}>$= arccos (2/(3A)) with A the mass number of the scattering material. For the antineutrinos of geophysical interest, the neutron travels of a few cm between the locations of positron creation and neutron absorption.

Therefore development of large fiducial volume, antineutrino detector set up with sub-MeV threshold and directional sensitivity will allow us to map the radiogenic heat sources in the mantle and to settle the question if the Earth has a planetary-scale nuclear reactor at its centre.

Proposed Underground Antenna at Curaçao

We would like to propose an underground antenna to investigate the internal state of the Earth. The initial antenna should be built on Curaçao. The geology of Curaçao, as studied by Klaver (1987), indicates that Curaçao is a mantle plume originating from the boundary of the core and the mantle, some 80 Ma ago. Sample analysis by Klaver (1987) indicates that the Curaçao basalt is more than an order of magnitude lower in K, Th, and U compared to sands in, e.g., The Netherlands.

Curaçao is more than 1000 km away from the Florida power reactors and from the mountain ranges of the Andes. It provides a very low background of natural radionuclides, and because it is surrounded by a considerable mass of oceanwater, the antineutrino flux from crustal sources and power reactors will be strongly reduced. That means that the antenna set up will be especially sensitive to antineutrino sources from the mantle and a possible geo-reactor. We expect that the calculations for Hawaii will be more or less indicative for Curaçao.

The creation of such an underground laboratory will be quite unique and will also include some technological challenges. One of them is drilling into basalt; the other is the development of low-energy dissipating electronics. Despite Curaçao being a plume sticking out of the ocean floor and cooled by ocean water at a depth of about 1 km, high temperatures are expected. In the underground laboratory we expect a high density of electronic devices in the detector setup. Since additional cooling is complicated, low-energy dissipating electronics will be required. Low-energy dissipating electronics is directly linked to the telecommunication technology and its industry.

It should be noted that the geological formation of the island of Curaçao would allow calibration of an antineutrino detector with the aid of nuclear power driven vessels, which could be

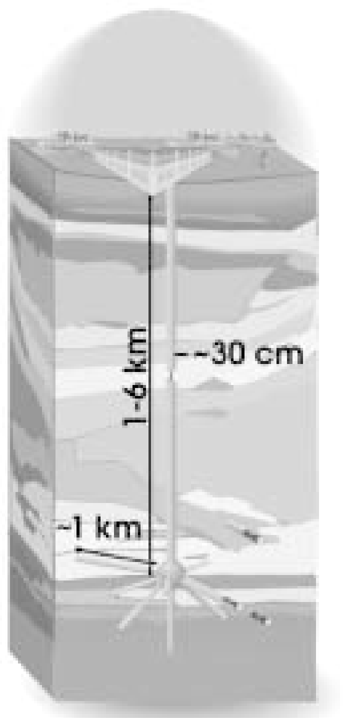

Figure 5. *Schematic presentation for an underground antenna for antineutrinos. The ultimate depth of the main shaft and the length of the secondary shaft will be determined on the basis of tests of the directionality and the efficiency of the prototype detectors.*

positioned at various locations and at variable distances from the detector.

The proposal foresees, as schematically depicted in Figure 5, in a vertically drilled main shaft of about 30 to 40 cm diameter until a depth where the detectors are not too sensitive to the muonic background. From a central point a set of 20 to 30 secondary shafts, 10 to 20 cm diameter and 0.5 to 1 km long, will be drilled by state of the art oil- and gas drilling techniques. Each secondary shaft will be loaded by a chain of antineutrino detectors and their associated data analysis and data transfer electronics.

The proposal will be carried out in a step-by-step approach with clear go-nogo decisions and associated funding. We have started in collaboration with iThemba LABS and University of Cape Town to test in the laboratory the properties of a candidate scintillator using standard electronics including coincidence and pulse-shape analyses. In next steps the directional sensitivity of the detectors will be examined at a nuclear power station and the standard electronics have to be converted to microprocessors. Before drilling the set-up will be tested in underground mine shafts.

In the end, we anticipate a world wide net of about ten antennas to tomographically image our planet. Such a global set-up will also serve as a very large base antenna system for antineutrinos produced in supernovae and gamma-ray bursts. In addition to their directional sensitivity, detection of antineutrinos will not be hampered by the overwhelming flux of solar neutrinos.

We invite interested people with expertise in one of these fields, who would like to participate in this proposed project to contact us.

This project is referred to as CURACAO (Curaçao Underground Research Arena for Core Antineutrino Observations). The authors would like to acknowledge the stimulating discussions with F. Brooks, H. R. Butcher, A. E. L. Dieperink, J. M. Herndon, P. Hoyng, G. Th. Klaver and F. R. Smit.

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