Geoneutrinos and heat production in the Earth

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Plate Tectonics, Convection, Geodynamo

Radioactive decay driving the Earth’s engine!

K, Th & U!
Nature & amount of Earth’s thermal power

*radiogenic heating vs secular cooling*

- abundance of heat producing elements (K, Th, U) in the Earth
  - estimates of BSE from 9TW to 36TW

- clues to planet formation processes
  - constrains chondritic Earth models

- amount of radiogenic power to drive mantle convection & plate tectonics
  - estimates of mantle 1.3TW to 28TW

  is the mantle compositionally layered? or has large structures?
  - layers, LLSVP, superplume piles

*the future is… Geoneutrino studies*
Disagreement with “chondritic” Earth Models

Murakami et al (May - 2012, *Nature*): “…the lower mantle is enriched in silicon … consistent with the [CI] **chondritic Earth model**.”

Campbell and O’Neill (March - 2012, *Nature*): “Evidence **against a chondritic Earth**”

Zhang et al (March - 2012, *Nature Geoscience*): The Ti isotopic composition of the **Earth and Moon overlaps that of enstatite chondrites**.

Fitoussi and Bourdon (March - 2012, *Science*): “Si isotopes support the conclusion that **Earth was not built solely from enstatite chondrites**.”

Warren (Nov - 2011, *EPSL*): “Among known chondrite groups, **EH yields a relatively close fit to the stable-isotopic composition of Earth**.”

- Compositional models differ widely, implying a **factor of three difference** in the U & Th abundances of the Earth
What is the composition of the Earth? and where did this stuff come from?

Heterogeneous mixtures of components with different formation temperatures and conditions

Planet:

mix of metal, silicate, volatiles
Sun and Chondrites are related

Carbonaceous (CI)

$K$, $Th$, & $U$ heat producing elements
Meteorite: Fall statistics
(n=1101)  (back to ~980 AD)

- Ordinary Chondrites 80%
- Iron meteorites
- Stony Iron meteorites
- Achondrites ~9%
- Carbonaceous Chondrites ~4%
- Enstatite Chondrites ~2%

Most studied meteorites fell to the Earth \( \leq 0.5 \text{ Ma ago} \)
U in the Earth:

"Differentiation"

~13 ng/g U in the Earth

Metallic sphere (core) <<<1 ng/g U

Silicate sphere 20* ng/g U

*O’Neill & Palme (2008) 10 ng/g
*Turcotte & Schubert (2002) 31 ng/g

Continental Crust 1300 ng/g U (~7 TW)

Mantle ~13* ng/g U (~13 TW)

*The Mantle could have as little 1-3 TW or as much as 28 TW
Earth’s surface heat flow $46 \pm 3 \ (47 \pm 1) \ TW$

- **Mantle cooling** ($18 \ TW$)
- **Crust R*** ($7 \pm 1 \ TW$) (Huang et al ‘13)
- **Mantle R*** ($13 \pm 4 \ TW$)
- **Core** ($\sim 9 \ TW$) (4-15 TW)

**Total R*** $20 \pm 4$

*R radiogenic heat (after McDonough & Sun ’95)

(0.4 TW) Tidal dissipation

Chemical differentiation

*after Jaupart et al 2008 Treatise of Geophysics*
Earth’s thermal evolution: role of K, Th & U

Arevalo, McDonough, Luong (2009) EPSL
What are Geoneutrinos?

- electron anti-neutrinos from the Earth, products of natural radioactivity

**Geoneutrino flux**
- typical flux $6 \times 10^6$ cm$^{-2}$ s$^{-1}$

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**What are Geoneutrinos?**

- Leptons
  - Quarks
  - Anti-neutrino vs neutrino

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**Force carriers**

- Gluon
  - Electroweak symmetry breaking (mass giving)
  - Outside of standard model
$\beta^-$ decay process (e.g., U, Th, K, Re, Lu, Rb)
Terrestrial Antineutrinos

\[ \bar{\nu}_e + p^+ \rightarrow n + e^+ \]

1.8 MeV Energy Threshold

Efforts to detect K geonus underway

Terrestrial antineutrinos from uranium and thorium are detectable
MeV-Scale Electron Anti-Neutrino Detection

Production in reactors and natural decays

Neutron-rich nucleus

Nucleus with one more proton and one less neutron

Key: 2 flashes, close in space and time, 2nd of known energy, eliminate background

Detection

$E_{\text{vis}} = E_\nu - 0.8 \text{ MeV}$

prompt

$E_{\text{vis}} = 2.2 \text{ MeV}$
delayed

• Standard inverse $\beta$-decay coincidence
• $E_\nu > 1.8 \text{ MeV}$
• Rate and spectrum - no direction

Reines & Cowan
Antineutrinos - Geoneutrinos

$$\bar{\nu}_e + p^+ \rightarrow n + e^+$$

- Ideal spectrum, assuming Th/U = 4 and closest reactor ~1000 km
- 238U
- 232Th
- Threshold MeV limit
- Commercial reactor

DETCTION RATE $dN/dE$
(kiloton yr keV)$^{-1}$

NEUTRINO ENERGY (MeV)
• **KamLAND** was designed to measure reactor antineutrinos.

• Reactor antineutrinos are the most significant contributor to the total signal.
Present LS-detectors, *data update*

Borexino, Italy (0.3kt)

SNO+, Canada (1kt)

KamLAND, Japan (1kt)

14±4 counts from May ‘07 to Nov ‘12

116 $^{+28}_{-27}$ counts

From 9 Mar ‘02 to 20 Nov ‘12
Can Physics Help Geoscience?

**TNU:** geo-\( n^- \) event seen by a kiloton detector in a year
Summary of geoneutrino results

SILICATE EARTH MODELS

Cosmochemical: uses meteorites – 10 TW

Geochemical: uses terrestrial rocks – 20 TW

Geodynamical: parameterized convection – 30 TW
Geoneutrino Flux on Earth Surface

\[
\frac{d\phi(E_\nu, r)}{dE_\nu} = A \frac{dn(E_\nu)}{dE_\nu} \int_{V_\oplus} d^3r' a(r') \rho(r') P(E_\nu, |r - r'|) \frac{d^3r'}{4\pi|r - r'|^2}
\]

Activity and number of produced geoneutrinos

Volume of source unit

Abundance and density of the source unit

Survival probability function

Distance between source unit and detector

Earth structure (\(\rho\) and \(L\)) and chemical composition (\(a\))
Constructing a 3-D reference model Earth

assigning chemical and physical states to Earth voxels
Global Earth Reference Model

- 7 layers for the top 200 km
- Integrate 3 global models for the crust
- New crust model with uncertainties

Huang et al (2013) G-cubed
Uranium Abundance in Middle Continental Crust layer

Average middle Cont. Crust U abundance is $0.97^{+0.58}_{-0.36}$ µg/g

Rudnick and Gao (2003) 1.3 µg/g
Surfaces of each layer is defined by geophysical data (i.e., gravity and seismic).
Predicted Global geoneutrino flux based on our new Reference Model

Geoneutrino contributions to detectors

Near Field: six closest $2^\circ \times 2^\circ$ crustal voxels
Far Field = bulk crust – near field crust

Fractional contribution

<table>
<thead>
<tr>
<th>Total flux (TNU)</th>
<th>Near Field Crust</th>
<th>Far Field Crust</th>
<th>Mantle</th>
</tr>
</thead>
<tbody>
<tr>
<td>KamLAND 31</td>
<td>49%</td>
<td>28%</td>
<td></td>
</tr>
<tr>
<td>Borexino 40</td>
<td>44%</td>
<td>22%</td>
<td></td>
</tr>
<tr>
<td>SNO+ 40</td>
<td>40%</td>
<td>23%</td>
<td></td>
</tr>
<tr>
<td>Hanohano 12</td>
<td>19%</td>
<td>75%</td>
<td></td>
</tr>
</tbody>
</table>

Continental

Oceanic

Near Field: six closest $2^\circ \times 2^\circ$ crustal voxels
Far Field = bulk crust – near field crust
Existing data squeezing @ limit

Y-axis data is strictly from physics

X-axis data is strictly from geology

Intercept is mantle contribution

Intercept $^{+14.5}_{-7.4}$ (TNU)

Mantle contribution

Coincidences of intercepts
Future detectors?

LENA, EU (50kt)

JUNO China (20kt)

Hanohano International ocean-based (10kt)
Korean Underwater Neutrino Observatory

**Physic Goals**
- Mass hierarchy
- Proton Decay
- Oscillation mixing

**Geology Goals**
- Th & U abundance
- Thermal evolution

In addition, the instrument can be used for Nuclear Monitoring Goals
Hanohano

A Deep Ocean
\( \bar{\nu}_e \) Electron Anti-Neutrino Observatory

Descent/ascent 39 min

An experiment with joint interests in Physics, Geology, and Security

Size: scalable from 1 to 50 kT
10-yr cost est: $250M @ 10 kT

- multiple deployments
- deep water cosmic shield
- control-able L/E detection
What’s hidden in the mantle?

Seismically slow “red” regions in the deep mantle

Can we image it with geonuses?

From Alan McNamara after Ritsema et al (Science, 1999)
Testing Earth Models

Mantle geoneutrino flux ($^{238}\text{U} \& ^{232}\text{Th}$)

Predicted geoneutrino flux

Mantle flux at the Earth’s surface

Total flux at surface dominated by Continental crust

Mantle flux at the Earth’s surface dominated by deep mantle structures


Ocean based experiment!

- Neutrino Imaging
- Pacific Transect
- Avoid continents
- 4 km depth deployments
- Map out the Earth’s interior
- Test Earth models

SUMMARY
Earth’s radiogenic (Th & U) power

- 22 ± 12 TW - Borexino
- 11.2 +7.9 -5.1 TW - KamLAND

Prediction: models range from 8 to 28 TW (for Th & U)

On-line and next generation experiments:
- SNO+ online 2015 😊
- JUNO: 2020, good experiment, big bkgd, geonu ...
- Hanohano: this is FUNDAMENTAL for geosciences
  Geology must participate & contribute to the cost

Future:
- Neutrino Imaging of Earth’s deep interior 😊
Geoneutrinos: ongoing efforts and wish list

Out-reach efforts

- Directionality
- $^{40}$K geonus
- Detecting hidden objects in the Earth

Geoneutrino

Geoneutrino is an electron antineutrino emitted in $\beta^-$ decay of a radionuclide naturally occurring in the Earth. Neutrinos are the lightest of the known subatomic particles. They lack measurable electromagnetic properties and dominantly interact via the weak nuclear force.

Matter is virtually transparent to neutrinos and consequently they travel, unimpeded, at near light speed through the Earth from their point of emission. Collectively geoneutrinos carry the integrated information about the abundances of their radioactive sources inside the Earth.

Extracting a geologically useful information (e.g., abundances of individual geoneutrino producing elements and their spatial distribution in Earth’s interior) from geoneutrino measurements is a major objective of the emerging field of neutrino geophysics.

Most geoneutrinos originate from $\beta^-$ decay branches of $^{40}$K, $^{232}$Th and $^{238}$U. Together these decay chains account for more than 99% of the present day radiogenic heat generated inside the Earth. Only geoneutrinos from $^{232}$Th and $^{238}$U decay chains are detectable by the inverse beta decay mechanism because these have the highest energies, i.e., $>1.8$ MeV (megaelectronvolts), the energy needed to transform a proton into a neutron and a positron.

The flashes of light generated from this interaction are recorded by large underground liquid scintillator detectors of neutrino experiments. To date, geoneutrino measurements at two sites, as reported by the KamLAND and Borexino collaborations, begin to place constraints on the...