Geoneutrinos and SNO+

Mark Chen
Queen’s University and CIFAR
What are Geoneutrinos?

The antineutrinos produced by natural radioactivity in the Earth

Radioactive decay of uranium, thorium and potassium-40 (the most significant heat-producing elements in the Earth) emits antineutrinos

\[ \bar{\nu}_e \]

Goal: assay the entire Earth by looking at its “neutrino glow”
Important Questions in Geosciences

- what is the radiogenic contribution (U, Th, $^{40}$K) to heat flow and energetics in the deep Earth?
  - geoneutrinos can measure (U and Th for now)
- are the fundamental ideas about Earth’s chemical origin correct?
- are the basic models of the composition of the crust correct?
  - geoneutrinos can test
- distribution of reservoirs in the mantle?
  - homogeneous or layered?
- nature of the core-mantle boundary?
- radiogenic elements in the core?
  - in particular potassium
- what is the planetary K/U ratio?
  - if we could detect $^{40}$K geoneutrinos…

neutrinos might probe
Earth’s Total Surface Heat Flow

Conventional Value
46±3 TW
but in 2005, a different estimate**
31±1 TW

**Hofmeister and Criss did not like that models of oceanic crust heat flux over-predict heat flow compared to measured oceanic samples (which are sparse compared to the continents), explained away by hydrothermal circulation; prefer lower flux

- Conductive heat flow measured at bore holes:
  - temperature gradient
  - conductivity

\[ Q = -k \frac{dT}{dx} \]
Earth’s surface heat flow (total 46 ±3)

- Radiogenic heat, mantle 12-14 TW
- Core heat flow 9±6 TW
- Secular cooling 18±10 TW
- Tidal dissipation, Chemical differentiation ~0.4 TW

breakdown of what we think gives rise to the measured heat flow

slide from Bill McDonough
Mantle convection models typically assume mantle Urey ratio: 0.4 to 1.0, generally ~0.7

Geochemical models predict mantle Urey ratio: 0.3 to 0.5
Urey Ratio and Mantle Convection Models

\[
\text{Urey ratio} = \frac{\text{radioactive heat production}}{\text{heat loss}}
\]

★Mantle convection models typically assume mantle Urey ratio: 0.4 to 1.0, generally \(~0.7\)

★Geochemical models predict mantle Urey ratio: 0.3 to 0.5
Discrepancy?

- estimated total heat flow 46 or 31 TW
  estimated radiogenic heat production 20 TW or 31 TW
  gives Urey ratio \(~0.3\) to \(~1\)

- Where are the problems?
  - Mantle convection models?
  - Total heat flow estimates?
  - Estimates of radiogenic heat production rate?

- Geoneutrino measurements can help constrain the planetary radiogenic heat production
## Uranium, Thorium and Potassium Decay

<table>
<thead>
<tr>
<th>Decay</th>
<th>$T_{1/2}$ [10$^9$ yr]</th>
<th>$E_{max}$ [MeV]</th>
<th>$Q$ [MeV]</th>
<th>$\epsilon_{\bar{\nu}}$ [kg$^{-1}$s$^{-1}$]</th>
<th>$\epsilon_H$ [W/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{U} \rightarrow ^{206}\text{Pb} + 8 , ^4\text{He} + 6e + 6\bar{\nu}$</td>
<td>4.47</td>
<td>3.26</td>
<td>51.7</td>
<td>$7.46 \times 10^7$</td>
<td>$0.95 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{232}\text{Th} \rightarrow ^{208}\text{Pb} + 6 , ^4\text{He} + 4e + 4\bar{\nu}$</td>
<td>14.0</td>
<td>2.25</td>
<td>42.7</td>
<td>$1.62 \times 10^7$</td>
<td>$0.27 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{40}\text{K} \rightarrow ^{40}\text{Ca} + e + \bar{\nu}$ (89%)</td>
<td>1.28</td>
<td>1.311</td>
<td>1.311</td>
<td>$2.32 \times 10^8$</td>
<td>$0.22 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Table from G. Fiorentini

- note: $^{40}\text{K}$ also has 10.72% EC branch
  - thus also emits neutrons as well as antineutrinos, but they are mostly inconsequential because of lower energy (EC to excited state of $^{40}\text{Ar}$) and smaller branching ratio

\[ \text{EC} \quad 10.72\% \quad ^{40}\text{K} \quad \beta^- \quad ^{40}\text{Ca} \]

$Q_{\beta^{-}} = 1311.09$  
$Q_{\text{EC}} = 1504.9$

0.0117% isotopic abundance
Neutrino Geoscience: General Concept

- measure the geoneutrino flux
- identify U, Th, $^{40}$K (if possible) from the energy of the neutrinos
- heat generation is directly related to number of geoneutrinos detected
- neutrino detectors need to have 100’s to 1000’s tonnes of target material for an appreciable rate of neutrino interactions
- a good target is an organic liquid scintillator – material that gives off light when struck by particles/radiation
How to Detect Geoneutrinos

- inverse beta decay: \( \bar{\nu}_e + p \rightarrow e^+ + n \)
  - respectable cross section on protons
  - threshold \( E > 1.8 \text{ MeV} \)
  - liquid scintillator is \( \sim \text{CH}_2 \) hence lots of protons
    - positron makes first scintillation
    - neutron captures on H
      - mean capture time \( \sim 0.2 \text{ ms} \)
    - delayed 2.2 MeV gamma ray from neutron capture makes second scintillation
- distinctive signature helps rejects background counts
  - \( e^+ \) and n correlated in time and in position in the liquid scintillator detector

Unfortunately, can’t detect \( ^{40}\text{K} \) geoneutrinos with this reaction…
Chemical Composition of the Earth

- chondrites are primitive meteorites
- thought to represent the primordial composition of the solar system
- why?
  - relative element abundances in CI carbonaceous chondrites matches that in the solar photosphere for “refractory elements”
- U and Th are refractory elements
- K is moderately volatile
  - K/U is important in geology, independent of radioactivity
  - K/U \( \sim 1 \times 10^4 \) in crustal rocks
  - K/U \( \sim 8 \times 10^4 \) in meteorites
  - where is the “missing” K? (and what effect on Earth’s thermal history?)
  - is potassium in the core? important for energetics of the core, heat flux and plumes from the CMB, geodynamo
Composition of the Primitive Mantle

Volatility trend @ 1AU from Sun

Lithophile Elements

(abundances relative to CI chondrite and Mg-normalized)

log 50% condensation Temperature (K) at 10^{-4} atms

slide from Bill McDonough
Composition of the Primitive Mantle

Volatility trend @ 1AU from Sun

slide from Bill McDonough
all the data points (dots) are each an element

the outliers are labeled

Solar photosphere (atoms Si = 1E6)

Cl carbonaceous chondrite (atoms Si = 1E6)
Bulk Silicate Earth – BSE

- the Earth forms from accreting primordial material in the solar system, an iron metal core separates and compatible metals go into the core
- but U, Th (and K?) are lithophile; they prefer to be in the silicate or molten rock around the iron core
- can thus estimate the amount of U and Th in the “primitive mantle” using chondrites, the size of the Earth, after core-mantle differentiation → this is the “Bulk Silicate Earth” model
- …then, the crust becomes enriched in U, Th and K because of the chemistry of rock at high pressures, resulting in a mantle that is further depleted (compared to BSE concentrations)
Bulk Silicate Earth – BSE

- The Earth forms from accreting primordial material in the solar system, an iron metal core separates and compatible metals go into the core.
- But U, Th (and K?) are lithophile; they prefer to be in the silicate or molten rock around the iron core.
- Can thus estimate the amount of U and Th in the “primitive mantle” using chondrites, the size of the Earth, after core-mantle differentiation → this is the “Bulk Silicate Earth” model.
- …Then, the crust becomes enriched in U, Th and K because of the chemistry of rock at high pressures, resulting in a mantle that is further depleted (compared to BSE concentrations).
the Earth forms from accreting primordial material in the solar system, an iron metal core separates and compatible metals go into the core

but U, Th (and K?) are lithophile; they prefer to be in the silicate or molten rock around the iron core

can thus estimate the amount of U and Th in the “primitive mantle” using chondrites, the size of the Earth, after core-mantle differentiation → this is the “Bulk Silicate Earth” model

…then, the crust becomes enriched in U, Th and K because of the chemistry of rock at high pressures, resulting in a mantle that is further depleted (compared to BSE concentrations)
K, Th & U in the Continental Crust

Enriched by factor 100 over Primitive Mantle

Compositional models for the bulk continental crust

Cont. Crust ~ 0.6% by mass of silicate earth

slide from Bill McDonough
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

Continental Crust 1000 ng/g U

Mantle 10 ng/g U

Chromatographic separation Mantle melting & crust formation
Geoneutrino Earth Models

- start with the BSE
- take reference values for composition of continental and oceanic crust (these come from rock samples)
- subtract the crust from the BSE to get the present “residual” mantle
- because continental and oceanic are so different, need to use a map of the crust (thickness and crust type) to calculate expected flux at different locations (of detectors in the world)

Table 1. Uranium and thorium abundances in the Earth.

<table>
<thead>
<tr>
<th></th>
<th>$^{238}\text{U}$ in ppm</th>
<th>$^{232}\text{Th}$ in ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Silicate Earth</td>
<td>0.0203</td>
<td>0.0795</td>
</tr>
<tr>
<td>average continental crust</td>
<td>1.4</td>
<td>5.6</td>
</tr>
<tr>
<td>average oceanic crust</td>
<td>0.10</td>
<td>0.22</td>
</tr>
<tr>
<td>present-day “residual” mantle</td>
<td>0.013</td>
<td>0.052</td>
</tr>
</tbody>
</table>

from C. Rothschild, M. Chen and F. Calaprice 1998

$T/U = 4$
CRUST 5.1 Map of Type and Thickness

Mooney, Laske, Masters (1998)
Antineutrino geophysics with liquid scintillator detectors

Casey G. Rothschild, Mark C. Chen and Frank P. Calaprice

Physics Department, Princeton University Princeton, New Jersey

Abstract. Detecting the antineutrinos emitted by the decay of radioactive elements in the mantle and crust could provide a direct measurement of the total abundance of uranium and thorium in the Earth. In calculating the antineutrino flux at specific sites, the local geology of the crust and the background from the world’s nuclear power reactors are important considerations. Employing a global crustal map, with type and thickness data, and using recent estimates of the uranium and thorium distribution in the Earth, we calculate the antineutrino event rate for two new neutrino detectors. We show that spectral features allow terrestrial antineutrino events to be identified above reactor antineutrino backgrounds and that the uranium and thorium contributions can be separately determined.
Geoneutrino Flux & Reactor Background

from Fiorentini, Mantovani, et al.

KamLAND near Kamioka, Japan

SNO+ near Sudbury, Canada

Borexino near L’Aquila, Italy

nuclear reactor background
KamLAND and Borexino

- large volume of liquid scintillator
- surrounded by photomultiplier tubes that detect the flashes of light (scintillation) produced by neutrino interactions
- immersed in/surrounded by pure water that functions as background radiation shielding
- located deep underground (e.g. in a mine) to reduce cosmic rays
KamLAND First Detection in 2005

Expected Geoneutrinos
- U-Series : 14.9
- Th-Series : 4.0

Backgrounds
- Reactor : 82.3±7.2
- (α,n) : 42.4±11.1
- Accidental : 2.38±0.01

BG total : 127.4±13.3
Observed : 152

Number of Geoneutrinos: $25^{+19}_{-18}$

“expected” geoneutrinos means from BSE models
KamLAND 2008 Geoneutrino Results

- factor two more data
- $^{13}$C(α,n) background error reduced
- improved reconstruction (off-axis calibration)
- larger fiducial volume
- accounting for reactor background time variations

$\Phi (U+Th \ geo-\nu) = (4.4 \pm 1.6) \times 10^6 \ cm^{-2} \ s^{-1}$

Th/U mass ratio fixed to 3.9 in the fit to the data
what geoscience have we learned from these observations?
Borexino and KamLAND versus BSE

- using Rothschild, Chen, Calaprice BSE
  - Borexino: 3.6 events/(100 tonne-yr)
  - KamLAND: 29 events/(1000 tonne-yr)

- measured
  - Borexino: $3.9^{+1.6}_{-1.3}$ events/(100 tonne-yr)
  - KamLAND: 25 ± 9 events/(1000 tonne-yr)

geoneutrino measurements are consistent with BSE-predicted values...

N.B. This slide is just for fun...not to be interpreted too rigorously!
Geoscience from KamLAND 2008

- measured flux consistent with the “Bulk Silicate Earth” model
- 99% CL upper limit to the geoneutrino flux, fixing the crust contribution, gives heat < 54 TW

from Sanshiro Enomoto
KamLAND 2011

- July 2007 earthquake – extended shutdown of Kashiwazaki-Kariwa nuclear power station (largest source of reactor antineutrinos in KamLAND)
- Purification of liquid scintillator ($^{210}$Pb and $^{210}$Po)
  - $^{13}$C($\alpha$,n)$^{16}$O background down by factor ~20
- Total exposure ~5× increase from first 2005 paper

Observed : 841
BG total : 729.4±32.3
Geoneutrino : $111^{+45}_{-43}$

just from the excess event rate
KamLAND 2011 Analysis cont’d

- Geoneutrino rate versus varying reactor background shows definite excess
- Fixing Th:U = 3.9; energy spectrum and time fit extracts \(106^{+29}_{-28}\) geoneutrino events

- Fully consistent with BSE predictions

Shaded band is the BSE model prediction

Combining Borexino and KamLAND, including crustal uncertainties (needed to interpret mantle “deep Earth” component), KamLAND paper finds 20 ± 9 TW (total heat from U and Th)
Is BSE all there is?

- model based upon enstatite chondrites recently published
- Javoy: K 150 ppm, Th 45 ppb, and U 11.5 ppb
- BSE: K 280 ppm, Th 80 ppb, and U 20 ppb
Stones from Space

Chondrites are primitive, undifferentiated, stony meteorites

**Enstatite Chondrite (EH)**
- O isotopic composition
- High Fe content
- Low in oxidized Fe

**Carbonaceous Chondrite (CI)**
- Composition solar photosphere
- Low metallic Fe content
- High in oxidized Fe

Depleted in volatile elements

Highest in volatile elements

Which one is Earth analogue?

slide from Steve Dye
Selected Silicate Earth Models

- Chemical earth models
  - EH chondrite- Javoy et al., 2010
    - 11-14 TW heating
  - CI chondrite- Rocholl, Jochum, 1993
    - 17-19 TW heating

- Physical earth models
  - Mantle convection- Turcotte et al., 2001
    - 27-35 TW heating
SNO+ Collaboration

Queen’s, Alberta, Laurentian, SNOLAB, TRIUMF
BNL, Penn, Washington, AASU, BHSU, UNC
Oxford, Sussex, QMUL, Leeds, Liverpool, Sheffield
LIP Lisbon
TU-Dresden
SNO+ Physics Program

- search for neutrinoless double beta decay
- neutrino physics
  - solar neutrinos
  - geo antineutrinos
  - reactor antineutrinos
  - supernova neutrinos

SNO+ Physics Goals
Sudbury Neutrino Observatory

1000 tonnes $D_2O$ → 780 tonnes liquid scintillator

12 m diameter Acrylic Vessel

18 m diameter support structure; 9500 PMTs (~60% photocathode coverage)

1700 tonnes inner shielding $H_2O$

5300 tonnes outer shielding $H_2O$

Urylon liner radon seal

depth: 2092 m (~6010 m.w.e.) ~70 muons/day
1000 tonnes $\text{D}_2\text{O}$

12 m diameter Acrylic Vessel

18 m diameter support structure; 9500 PMTs (~60% photocathode coverage)

1700 tonnes inner shielding $\text{H}_2\text{O}$

5300 tonnes outer shielding $\text{H}_2\text{O}$

Urylon liner radon seal

depth: 2092 m (~6010 m.w.e.) ~70 muons/day
Sudbury Neutrino Observatory

1000 tonnes $D_2O$ → 780 tonnes liquid scintillator

12 m diameter Acrylic Vessel

18 m diameter support structure; 9500 PMTs (~60% photocathode coverage)

1700 tonnes inner shielding $H_2O$

5300 tonnes outer shielding $H_2O$

Urylon liner radon seal

hold down rope net

depth: 2092 m (~6010 m.w.e.) ~70 muons/day
Geoneutrinos in SNO+

- KamLAND: 33 events per year (1000 tons CH\(_2\)) / 142 events reactor
- SNO+: 44 events per year (1000 tons CH\(_2\)) / 38 events reactor

SNO+ geoneutrinos and reactor background

*note: scaled to the same target so as to compare geology*
1. geoneutrino measurement
2. any local geology impacting my interpretation?
3. compare with the predicted main signal component from the surrounding continental crust
4. how is our understanding of the averaged composition of the continents?
5. lastly, subtract off these well-characterized expectations to get the deep Earth component to test global composition (e.g. BSE)
Continental Crust Questions

- we can sample the crust…but not completely
  - rock samples are used to determine the composition of the crust but depth variations not easily sampled
  - are the basic ideas correct about the formation of continents and how concentrations are enriched compared to the mantle?
    - e.g. average continental crust compositional model is 25% “Andesite” and 75% Archaen [R. Rudnick] – is this consistent with geoneutrino measurements?
- geoneutrinos could perform an integrating survey of the continental crust, especially in a location where the crust structure is well understood
Local Geology around Sudbury

maybe the best understood piece of crust in the world because of:

- mining and mineral prospecting in the area
- many deep bore holes (some of the deepest) are nearby
- extensive studies with seismic transects in the vicinity (Lithoprobe)
- heat flow measurements all through the Canadian Shield
- airborne gamma ray maps (uranium prospecting)
- tilted and uplifted continental crust nearby (Kapuskasing)
  - allows some study of the vertical profile to access the lower crust composition
- regional geology facilitated because of exposed rocks
- the regional geology is also relatively simple and relatively uniform
maybe the best understood piece of crust in the world because of:

- mining and mineral prospecting in the area
- many deep bore holes (some of the deepest) are nearby
- extensive studies with seismic transects in the vicinity (Lithoprobe)
- heat flow measurements all through the Canadian Shield
- airborne gamma ray maps (uranium prospecting)
- tilted and uplifted continental crust nearby (Kapuskasing)
- allows some study of the vertical profile to access the lower crust composition
- regional geology facilitated because of exposed rocks
- the regional geology is also relatively simple and relatively uniform
maybe the best understood piece of crust in the world because of:

- mining and mineral prospecting in the area
- many deep bore holes (some of the deepest) are nearby
- extensive studies with seismic transects in the vicinity (Lithoprobe)
- heat flow measurements all through the Canadian Shield
- airborne gamma ray maps (uranium prospecting)
- tilted and uplifted continental crust nearby (Kapuskasing)

allows some study of the vertical profile to access the lower crust composition

regional geology facilitated because of exposed rocks

the regional geology is also relatively simple and relatively uniform

Local Geology around Sudbury
Local Geology around Sudbury

maybe the best understood piece of crust in the world because of:

- mining and mineral prospecting in the area
- many deep bore holes (some of the deepest) are nearby
- extensive studies with seismic transects in the vicinity (Lithoprobe)
- tilted and uplifted continental crust nearby (Kapuskasing)
- allows some study of the vertical profile to access the lower crust composition
- regional geology facilitated because of exposed rocks
- the regional geology is also relatively simple and relatively uniform

Enhanced crustal geo-neutrino production near the Sudbury Neutrino Observatory, Ontario, Canada

H.K.C. Perry a, J.-C. Mareschal a,*, C. Jaupart b

a GEOTOP-UQAM-McGill, Université du Québec à Montréal, Canada
b Institut de Physique du Globe de Paris, France
Local Geology around Sudbury

maybe the best understood piece of crust in the world because of:

- mining and mineral prospecting in the area
- many deep bore holes (some of the deepest) are nearby
- extensive studies with seismic transects in the vicinity (Lithoprobe)
- 

\[ \pi \]

allows some study of the vertical profile to access the lower crust composition

- regional geology facilitated because of exposed rocks
- the regional geology is also relatively simple and relatively uniform
Local Geology around Sudbury

surface heat flow map around Sudbury (Perry et al.)
Local Geology around Sudbury

Gamma-ray spectroscopy

Equivalent U (µg/g)

Data courtesy of Canadian Geological Survey
Turning SNO into SNO+

- to do this we need to:
  - buy the liquid scintillator
  - install hold down ropes for the acrylic vessel
  - build a liquid scintillator purification system
  - clean up inside of the Acrylic Vessel (remove radon daughters)
  - minor upgrades to the cover gas
  - minor upgrades to the DAQ/electronics
  - change the calibration system and sources
Draining SNO and Boating Inspections
SNO+ Rope Hold Down Net

SNO+ ropes will be Tensylon: low U, Th, K ultra-high molecular weight polyethylene
SNO+ Rope Hold Down Net

rope tension calculation and visualization of net-PSUP geometry

SNO+ ropes will be Tensylon: low U, Th, K ultra-high molecular weight polyethylene
all SNO+ cavity access is via bosun’s chair down a single hatch

work in cavity under an “umbrella” tarp to keep dirty work from contaminating clean detector above

negative air pressure below tarp
all SNO+ cavity access is via bosun’s chair down a single hatch

work in cavity under an “umbrella” tarp to keep dirty work from contaminating clean detector above
Entering the SNO Cavity – Bosun’s Chair
Entering the SNO Cavity – Bosun’s Chair
Entering the SNO Cavity – Bosun’s Chair
Entering the SNO Cavity – Bosun’s Chair
The Umbrella
February 15th 2011

access tube
Drilling Inside the SNO+ Cavity

drilling to install anchors for the hold-down net

in the SNO+ cavity, under the umbrella
Time Lapse in the Cavity
Time Lapse in the Cavity
All Done!

Floor liner replacement
All Done!

Floor liner replacement
New SNO+ Floor Liner

new floor liner sprayed including up the sides of the walls and over the anchor plates
AV Sanding Tower

SNO+ Preparation

- Sanding AV
- Replacing non-functional PMTs
- Electronics rehabilitation
- New calibration systems
- New purification system
- Improved cover gas system
- New glove box
AV Sanding Tower

- Sanding AV
- Replacing non-functional PMTs
- Electronics rehabilitation
- New calibration systems
- New purification system
- Improved cover gas system
- New glove box
- AV bottom cleaning ladder
SNO+ Status

- cavity hold down anchors and new floor complete
- new rope net delivered to site, preparing for installation in January 2012
- scintillator purification system columns, vessels, heat exchangers being fabricated, ready for installation in mid-2012
- clean up inside the Acrylic Vessel (remove radon daughters)
  - preparing to install inside AV access tower
- minor upgrades to the cover gas underway
- new electronics installed; running with new DAQ
- preparing for water-filled detector commissioning runs in mid-2012

- target date for start of scintillator filling: January 2013
Summary

- Geoneutrinos are a new frontier in Earth Sciences
  - ...we are just getting started with detecting geoneutrinos and using them to explore fundamental questions

- SNO+ will be the forefront geoneutrino detector in the next few years...so hang on and stay tuned!