Earth models and primordial heat
... and geonu emission from deep mantle piles

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Present-day dynamics
Quantify major energy terms
Earth’s bulk composition
Spatial distribution of radioactivity
Geoneutrino constraints
Building blocks

Solar nebula

Planetary formation

Early differentiation processes
  First few 100 My
  Core formation
  Magma ocean

Ongoing dynamic evolution
  Chemical fractionation vs. homogenization
  Crust formation
  Subduction
  Mantle, core dynamics

Solar System formation → Present-day Earth
Planetary formation

Solar nebula composition
   Big Bang (H, He, Li) + stellar (higher Z) nucleosynthesis

Compositional gradients, heterogeneity in the cooling solar nebula?
   Condensation temperature, volatility
   U & Th refractory, K moderately volatile
Planetary formation

Last stage of planetary formation. Outcome of 4 simulations – planet position, radius, composition in terms of original heliocentric distance of material.

Chambers, EPSL 2011

Some memory of compositional gradient in the nebula
Planetary formation

Solar nebula composition
   Big Bang (H, He, Li) + stellar (higher Z) nucleosynthesis

Compositional gradients, heterogeneity in the cooling solar nebula?
   Condensation temperature, volatility
     U & Th refractory, K moderately volatile

Dust & gas to grains to planetesimals

Planetesimals to planetary embryos ~1 My

Last stage ~100 My
   Giant impacts
   Planet radial migration
The “Grand Tack Scenario”

Inward-then-outward migration of Jupiter, Saturn

Jupiter formed at ~3.5 AU

Spiraled inward to ~1.5 AU (present-day Mars orbit) due to gas drag

Then migrated outward to current location at 5.2 AU

Saturn experienced a similar sequence

- Can explain the small size of Mars
- Consistent with the existence of asteroidal belt
- May have rid the inner Solar System of volatiles
Planetary formation

Solar nebula composition
  Big Bang (H, He, Li) + stellar (higher Z) nucleosynthesis

Compositional gradients, heterogeneity in the cooling solar nebula?
  Condensation temperature, volatility
  **U & Th refractory, K moderately volatile**

Dust & gas to grains to planetesimals

Planetesimals to planetary embryos ~1 My

Last stage ~100 My
  Giant impacts
  Planet radial migration

Hot beginning
  Gravitational energy released upon accretion, differentiation

Extensive melting, magma ocean(s)

Incompatibility, solid vs. melt partitioning
  **U, Th, K incompatible, enter the melt**
Gravitational energy

of accretion – forming a homogeneous body

\[ E_g = 4\pi \int_0^R g(r)\rho(r)r^3\,dr \]

\[ E_{\text{acr}} = \frac{GM^2}{R} \]

Earth:

\[ \Delta T_{\text{acr}} = \frac{GM^2}{R} / (MC_P) \approx 5 \times 10^4 \, \text{K} \]

of differentiation – forming the core

\[ \Delta T_{\text{diff}} \approx 2000 \, \text{K} \]
Loosing primordial heat – Mantle cooling rate

petrological constraint based on inference of melting temperature of primitive mantle melts

inferred cooling rate of $50 \pm 25$ K/Gy translates into $8 \pm 4$ TW mantle heat output due to cooling
Giant impacts, Moon formation, magma ocean

From Hf–W chronology (Kleine et al. GCA 2009):
Core formation at ~30–100 My after beginning of Solar System
Moon formation

Deep magma ocean (metal–silicate equilibration at >400 km depth; Wood et al. Nature 2006)
**Siderophile** elements go in the core
**Lithophile** elements go in the silicate phase: *negligible in U, Th, K in the core*

Makes sense to talk about “Silicate Earth”
Composition of Silicate Earth (BSE)

- “Geochemical” estimate
- “Cosmochemical” estimate
- “Geodynamical” estimate
Composition of CI chondrites matches solar photospheric abundances in refractory lithophile, siderophile, and volatile elements.

Most primitive, highest volatile abundance of chondrites

Best representative of primordial nebular material
Geochemical BSE estimate(s)

Ratios of Refractory Lithophile Element abundances constrained by CI chondrites

Absolute RLE abundances and non-refractory element abundances inferred from available mantle & crustal rock samples

Uses petrological models on peridotite xenoliths, massif peridotites, primitive melts

McDonough & Sun (1995) ... 20 ± 4 ppb U
Allègre (1995) ... 21 ppb U
Hart & Zindler (1986) ... 20.8 ppb U
Palme & O’Neill (2003) ... 22 ± 3 ppb U

Results in \(~20\) TW radiogenic power in BSE
Cosmochemical BSE estimate

Isotopic similarity between Earth rocks and enstatite chondrides

Similarity in oxidation state

Build the Earth from E-chondrite material

Javoy et al. EPSL 2010 ... 12 ppb U

Gives ~11 TW radiogenic power in BSE

Also “collisional erosion” model  (O’Neill & Palme 2008)

Earth formed with “geochemical” abundances (22 ppm U in BSE)

Differentiated early crust (enriched in U, Th, K)

This crust was lost during a giant impact collision → 10 ppm U in BSE
Geodynamical BSE estimate

Based on energetics of mantle convection

Parameterized convection models:

heat loss = radiogenic heating + secular cooling

Classical scaling between \( Q_s \) (Nusselt number) and vigor of convection (Rayleigh number)

\[
Q_s(t) = H_{rad}(t) - C \frac{dT(t)}{dt}
\]

\( Nu \propto Ra(T)^{1/3} \)

Need a large proportion of radiogenic heating to account for mantle heat flow, otherwise “thermal catastrophe” in the Archean

Requires mantle Urey \( \geq 0.6 \) (geochemical = 0.3, cosmochemical = 0.1)

Therefore needs higher abundance of U, Th, K

Radiogenic heating \( \geq 30 \text{ TW in BSE} \)
**Composition of Silicate Earth (BSE)**

- **“Geochemical” estimate**
  - Ratios of RLE abundances constrained by C1 chondrites
  - Absolute abundances inferred from Earth rock samples

- **“Cosmochemical” estimate**
  - Isotopic similarity between Earth rocks and E-chondrides
  - Build the Earth from E-chondrite material
  - Javoy et al. (2010)
  - also “collisional erosion” models (O’Neill & Palme 2008)

- **“Geodynamical” estimate**
  - Based on a classical parameterized convection model
  - Requires a high mantle Urey ratio, i.e., high U, Th, K

**TW radiogenic power**

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<tr>
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<th>BSE</th>
<th>Mantle</th>
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<tr>
<td>U</td>
<td>20±4</td>
<td>12±4</td>
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<td>Th</td>
<td>11±2</td>
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<td>K</td>
<td>33±3</td>
<td>25±3</td>
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**BSE = Mantle + Crust**

- Oceanic:  0.22 ± 0.03 TW
- Continental: 7.8 ± 0.9 TW

Tomorrow: New crustal model by Yu Huang et al.

\[ CC = 6.8 \ (+1.4/-1.1) \ TW \]
How is radioactivity distributed in the mantle?

Educated hypothesis → Geoneutrino flux prediction → Testing with geoneutrino measurement
Mantle geoneutrino emission

\[ \Phi(r) = \frac{n_v \lambda P}{4\pi} \int_{\Omega} \frac{A(r') \rho(r')}{|r - r'|^2} \, dr' \]

Flux \( \Phi \) at position \( r \) from a given radionuclide distributed with abundance \( A \) in volume \( \Omega \)

Mantle geoneutrino U+Th signal prediction

- "UNIF" mantle

<table>
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<tr>
<th>TNU</th>
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<th>Geochemical</th>
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Shallow mantle composition

Mid-Oceanic Ridge Basalt composition →
source rock abundances in shallow mantle

MORB-source mantle abundance estimates

- Workman & Hart (2005) 2.8 ± 0.4
- Salters & Stracke (2004) 4.1 ± 1.2 TW
- Arevalo & McDonough (2010) 7.5 ± 1.5

Bulk mantle (=BSE–Crust)

- Cosmochemical 3.3 ± 2.0
- Geochemical 12 ± 4 TW
- Geodynamical 25 ± 3

Require enriched material in the mantle
Mantle geoneutrino emission

Uniform mantle

Enriched layer (10% of mantle)

Spherically symmetric U & Th distribution in the mantle

Mantle geoneutrino U+Th signal prediction

- "UNIF" mantle
- "EL" with A&McD DM
- "EL" with S&S DM
- "EL" with W&H DM

N/A
Mantle geoneutrino U+Th signal prediction

Uniform mantle
Enriched layer (10% of mantle)

Measurements
Combined analysis of detection at KamLAND and Borexino
(Bellini et al. arXiv:1303.2571)

+ new KamLAND data ??
Seismic tomography image of present-day mantle

Seismic shear wave speed anomaly
Tomographic model S20RTS (Ritsema et al.)

Two large scale seismic speed anomalies – below Africa and below central Pacific

Anti-correlation of shear and sound wavespeeds + sharp velocity gradients suggest a *compositional component*

“piles” or “LLSVPs” or “superplumes”

Candidate for a distinct chemical reservoir

Sat AM: Ed Garnero
Origin of deep mantle reservoir

Remnant of dense basal magma ocean at the bottom of the mantle?

Continuous recycled subducted slabs buried at core–mantle boundary?

Next talk: Dapeng Zhao

Remnant of dense basal magma ocean at the bottom of the mantle?

Labrosse et al. EPSL 2006
Thermochemical piles in deep mantle?

Assume these piles represent an enriched reservoir. δlnVs isocontours ⇒ shape

Mantle geoneutrino U+Th signal prediction

Can we detect such variation in mantle geonu flux?
To constrain mantle Th, U, we need to measure in the ocean.

Mantle contribution to total signal

Continental locations: not more than ~25% of geonu signal coming from mantle

O.Š., McDonough, Kite, Lekić, Dye, Zhong, EPSL 2013
Proposed two-site measurement in the Pacific

Mantle contribution to total signal

Prediction along 161°W meridian

O.Š., McDonough, Kite, Lekić, Dye, Zhong, EPSL 2013
Summary

• Process of planetary formation

• Hot beginning of the Earth

• Early differentiation events
  – core formation
  – early fractionation of silicate Earth?

• Three classes of BSE compositional models

  [Enstatite chondrite model inconsistent with geonu measurements (1σ) ?]

• Ocean site measurement needed to significantly constrain mantle radioactivity. Multiple-site to resolve lateral variations.