In 1897, Earth’s 1st order structure -- silicate shell surrounding metal core

Emil Johann Wiechert
1861-1928
The composition of the Earth?

How do we get it and how well is it known?

Models must be realistic and multiply constrained

Constraints include data from:
- geochemistry
- petrology
- thermodynamics
- meteorites
- mineral physics
- etc.

& Neutrino geophysics

What were the conditions ($P, T, f_{O2}$) – vs - time @ 1AU during accretion?
Mixing across ~1AU likely (chemical disequilibrium?)

Rapid formation of kilometer bodies from dust

Rapid Formation of Moon sized bodies by runaway accretion

Slow (~10 Ma) Formation of Earthlike Planets

Planet formation

Mixing across ~1AU likely (chemical disequilibrium?)
“Standard” Model

- Chondrites, primitive meteorites, are key
- So too, the composition of the solar photosphere
- Refractory elements (RE) in chondritic proportions
- Absolute abundances of RE – model dependent
- Mg, Fe & Si are non-refractory elements
- Chemical gradient in solar system
- Non-refractory elements – model dependent
- U & Th are RE, whereas K is moderately volatile
Meteorites

Achondrite, Ca-poor, Diogenite

Johnstown

Carbonaceous chondrite (CV3)

Imilac

Pallasite, mixture of olivine and iron

Allende

Henbury

IIIAB
• **Chondrites**: undifferentiated – rock & metal mixture

<table>
<thead>
<tr>
<th>Elements</th>
<th>siderophile</th>
<th>lithophile</th>
<th>chalcophile</th>
</tr>
</thead>
<tbody>
<tr>
<td>metals</td>
<td></td>
<td>silicates/oxides</td>
<td>sulfides</td>
</tr>
<tr>
<td>refractory</td>
<td>&gt;1400 K</td>
<td>~1300 K</td>
<td>&lt;1250 K</td>
</tr>
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</table>

• U & Th are refractory, K is moderately volatile, and all 3 are generally considered **lithophile** ……
Primitive Mantle =

Mantle + Crust
Define this first....

Composition of the Primitive Mantle

Planetary volatility trend @ 1AU

Lithophile Elements

(abundances relative to CI chondrite and Mg-normalized)

log 50% condensation Temperature (K) at 10^-4 atms
Composition of the Earth and chondrites

Earth

Oxygen

Iron

Silicon

Mg

other

atomic

mass

enstatite chondrites

ordinary chondrites

carbonaceous chondrites

Earth
Composition of the Earth

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

abundances relative to CI chondrite and Mg-normalized

Earth

moderately volatile elements

volatile elements

log 50% condensation Temperature (K) at 10^{-4} atms
Core elements left in the Silicate Earth

Siderophile and Chalcophile Elements

Siderophile Elements

Chalcophile Elements

Planetary volatility trend @ IAU

Core Subtraction

Log 50% condensation Temperature (K) at 10^-4 atms
4 most abundant elements in the Earth:

Fe, O, Si and Mg

6 most abundance elements in the Primitive Mantle:

- O, Si, Mg, and – Fe, Al, Ca

This result and 1\textsuperscript{st} order physical data for the core yield a precise estimate for the planet’s Fe/Al ratio: $20 \pm 2$
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
What’s in the core?

What would you like?

Constraints: density profile, magnetic field, abundances of the elements,

Insights from: cosmochemistry, geochemistry, thermodynamics, mineral physics, petrology, Hf-W isotopes (formation age)

How well do we know some elements?
Knowing the Earth's Fe content, in turn defines its bulk Ni, Co Cr and V content
# Core compositional models

<table>
<thead>
<tr>
<th></th>
<th>Model 1</th>
<th></th>
<th>Model 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Si-bearing</td>
<td>O-bearing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>wt.%</td>
<td>Earth</td>
<td>Core</td>
<td>Earth</td>
<td>Core</td>
</tr>
<tr>
<td>Fe</td>
<td>32.0</td>
<td>85.5</td>
<td>32.9</td>
<td>88.3</td>
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<tr>
<td>O</td>
<td>29.7</td>
<td>0</td>
<td>30.7</td>
<td>3</td>
</tr>
<tr>
<td>Si</td>
<td>16.1</td>
<td>6</td>
<td>14.2</td>
<td>0</td>
</tr>
<tr>
<td>Ni</td>
<td>1.82</td>
<td>5.2</td>
<td>1.87</td>
<td>5.4</td>
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<tr>
<td>S</td>
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<td>1.9</td>
<td>0.64</td>
<td>1.9</td>
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<tr>
<td>Cr</td>
<td>0.47</td>
<td>0.9</td>
<td>0.47</td>
<td>0.9</td>
</tr>
<tr>
<td>P</td>
<td>0.07</td>
<td>0.20</td>
<td>0.07</td>
<td>0.20</td>
</tr>
<tr>
<td>C</td>
<td>0.07</td>
<td>0.20</td>
<td>0.07</td>
<td>0.20</td>
</tr>
<tr>
<td>H</td>
<td>0.03</td>
<td>0.06</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>Mean atomic #</td>
<td>23.5</td>
<td></td>
<td>23.2</td>
<td></td>
</tr>
</tbody>
</table>

*Others*
Only ~2% sulfur in the outer core

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

Earth

abundances relative to CI chondrite and Mg-normalized

carbonaceous chondrites

$S_{OC} \leq 10\%$
Core formation
- when?
- how?

Siderophile Elements
(ideal abundances relative to CI chondrite and Mg-normalized)

Planetary volatility trend @ IAU

Siderophile Elements
(unstable abundances relative to CI chondrite and Mg-normalized)

Core formation
- when?
- how?
Tungsten Isotopic Age of CORE FORMATION

$\varepsilon^{182}_{\text{W}}$

Earth evolution

Chondritic line

data for Fe-meteorites

Years after $t_0$ (Ma)

after Yin & Jacobsen, Schoenberg et al, Kliene et al (all 2002)
Radioactive elements in the core

A case for understanding Core energetics

How does the energy balance of the core relate?

• Age of the inner core
• Radioactive heat sources in the core
• Chemical evolution of the core
• Deep Earth temperatures at core formation
• Magnitude and pattern of base heating for mantle convection
• Strength, structure, time-variation, and reversal history of the geodynamo
There is a need to understand the energy budget of the Earth

Global Energy Balance in the Outer Core

\[ Q_{CMB} = Q_{ICB} + Q_C + Q_L + Q_G + Q_R \]
\[ = (P_C + P_L + P_G) d\tau IC + Q_R \]

During Inner Core Growth:

Cooling
\[ \int_{0}^{r_{IC}} P_C d\tau IC \approx 20 \pm 16 \times 10^{28} J \]

Latent
\[ \int_{0}^{r_{IC}} P_L d\tau IC \approx 7 \pm 2 \times 10^{28} J \]

Gravitational
\[ \int_{6}^{r_{IC}} P_G d\tau IC \approx 4 \pm 2 \times 10^{28} J \]

\[ \Delta E_R - \int_{0}^{r_{IC}} Q_R d\tau IC \]

\[ \Delta E_{ICR}^0 = \int_{0}^{\infty} (P_C + P_L + P_G) d\tau IC + E_R \approx 31 \pm 20 \times 10^{28} J + \Delta E_R \]

Core Energetics

From Peter Olsen (JHU)
Potassium in the core?

Metal-Silicate Partitioning of Potassium

---

**This study**

- 3.6 GPa
- 7.7 GPa

CI-chondrite model composition
(Mg/Si=1.1, NBO/T=2.7, IW-2)
doped with 4.7 wt% K

Trend predicted by Murthy et al. (2003) for a silicate melt with NBO/T of 2.7

Data from Corgne, Fei & McDonough (2005) unpublished
Uranium in the core?

Data from Wheeler, Walker, Fei, Minarik & McDonough (2006) in press
Considerations

- The Earth is a work in progress

- The formation and evolution is fundamentally a product of both physical and chemical processes

- In general, the view from physics is an instantaneous one, whereas that from chemistry is a time integrated one

- Compositional models of the Earth and its reservoirs (core, mantle, crust) must address the balance of forces from various potentials
Conclusions

- The K, Th and U budget of the Earth is established by studies of samples of the crust and mantle and comsmochemical constraints.

- Th & U are refractory elements and thus constrained by abundances of like elements in the Earth.

- K is a moderately volatile element and its abundance in the Earth is established from the planetary volatility curve.

- Uncertainties in this analyses are sample dependent.
Unwary “readers” should take warning that ordinary language undergoes modification to a high-pressure form when applied to the interior of the Earth. A few examples of equivalents follow:

<table>
<thead>
<tr>
<th>High-pressure form</th>
<th>Ordinary meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>certain</td>
<td>dubious</td>
</tr>
<tr>
<td>undoubtedly</td>
<td>perhaps</td>
</tr>
<tr>
<td>positive proof</td>
<td>vague suggestion</td>
</tr>
<tr>
<td>unanswerable argument</td>
<td>trivial objection</td>
</tr>
<tr>
<td>pure iron</td>
<td>uncertain mixture of all the elements</td>
</tr>
</tbody>
</table>
Future challenges

- Understanding the Earth’s total dissipated power and its sources (Q & Urey ratio) --- K data!

- Conditions of core formation, core-mantle equilibrium and the distribution of radioactive elements

- State and composition of the deep Earth boundary layers (inner-outer core and core-mantle boundaries)

- We expect much from Neutrino Geophysics