Thermal history of the Earth's core

COME-IN meeting

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Introduction

- Study thermal evolution of the Earth's core and apply model to Mercury at a later time
- Thermal evolution of the Earth's core from the energy and entropy budgets
- Model based on Gubbins (2003,2004) and Davies 2015

What we know about Earth's core...

Outer core radius	$r_{CMB} = 3480$ km
Inner core radius	$r_{ICB} = 1221$ km
Density jump at the ICB $\Rightarrow$ light elements in the core: outer core inner core	$\Delta\rho = 0.8$ g.cm^{-3} 13 at.% O, 4 at.% S, 4 at.% Si 0.1 at.% O, 3 at.% S, 4 at.% Si
Geodynamo	at least for the last 3.5 Gyr

Problem: new higher (3x) thermal conductivity

$\Rightarrow$ enhances the heat conducted along the adiabat

$\Rightarrow$ less power available to generate dynamo

- likely stable stratification below the CMB $\Rightarrow$ influence on the magnetic field at the surface and on convection
- alternative energy source needed

One solution: light element exsolution (*O'Rourke and Stevenson, 2016*)

Energy budget

$$Q_{CMB} = Q_s + Q_L + Q_g + Q_P + Q_{PL} + Q_r$$

- CMB heat flux:

$$Q_{CMB} = -\oint k\vec{\nabla}T \cdot \vec{n}\,\mathrm{d}S$$

Energy budget

$$Q_{CMB} = Q_s + Q_L + Q_g + Q_P + Q_{PL} + Q_r$$

- CMB heat flux:

$$Q_{CMB} = -\oint k\vec{\nabla} T \cdot \vec{n}\, \mathrm{d}S$$

- Secular cooling:

$$Q_s = f_s(C_p, T)\frac{\mathrm{d}T_{CMB}}{\mathrm{d}t}$$

- Latent heat:

$$Q_L = f_L(L)\frac{\mathrm{d}T_{CMB}}{\mathrm{d}t}$$

- Gravitational energy:

$$Q_g = f_g(\alpha_c, \Delta c_{ICB})\frac{\mathrm{d}T_{CMB}}{\mathrm{d}t}$$

Entropy budget

$$E_J + E_k + E_a = E_s + E_L + E_g + E_P + E_{PL} + E_h + E_r$$

Entropy budget

$$E_J + E_k + E_a = E_s + E_L + E_g + E_P + E_{PL} + E_h + E_r$$

- Entropy of thermal conduction:

$$E_k = \int k \left(\frac{\nabla T_a}{T_a} \right)^2 \mathrm{d}V$$

- Secular cooling:

$$E_s = g_s(C_p, T, \rho) \frac{\mathrm{d}T_{CMB}}{\mathrm{d}T} + \frac{Q_s}{T_{CMB}}$$

- Latent heat:

$$E_L = Q_L \frac{T_{CMB} - T_{ICB}}{T_{ICB} T_{CMB}}$$

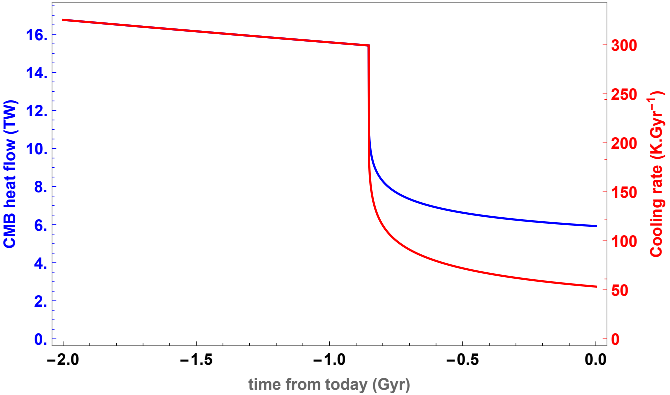
- Gravitational energy:

$$E_g = \frac{Q_g}{T_{CMB}}$$

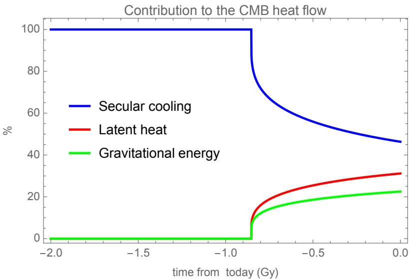
Marginal dynamo

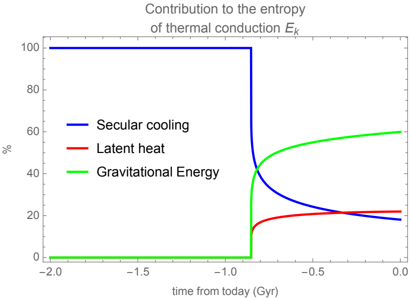
Marginal dynamo: $E_J = 0$

$$\Rightarrow \begin{cases} Q_{CMB} = Q_s + Q_L + Q_g \\ E_k = E_s + E_L + E_g \end{cases}$$



Heat flow and entropy contributions

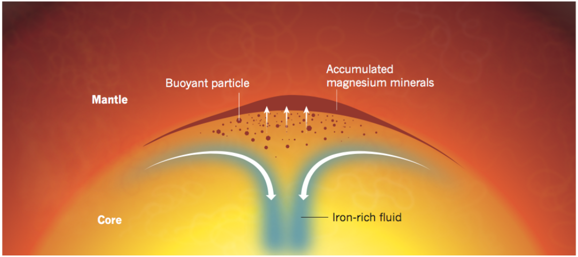




- IC age: $\sim$ 850 Myr
- Without IC: $Q_{CMB} = Q_s$ and $E_k = E_s$
- With IC: Q_s and E_g most important contributions

Magnesium precipitation

Problem: new higher thermal conductivity
⇒ enhances the heat conducted along the adiabat
⇒ alternative energy source is needed
One solution: light element exsolution (*O'Rourke and Stevenson, 2016*)



Energy balances

Marginal dynamo: $E_J = 0$

$$\Rightarrow \left\{ \begin{array}{ccc} Q_{CMB} & = & Q_s + Q_L + Q_g + Q_{g,Mg} \\ E_k & = & E_s + E_L + E_g + E_{g,Mg} \end{array} \right.$$

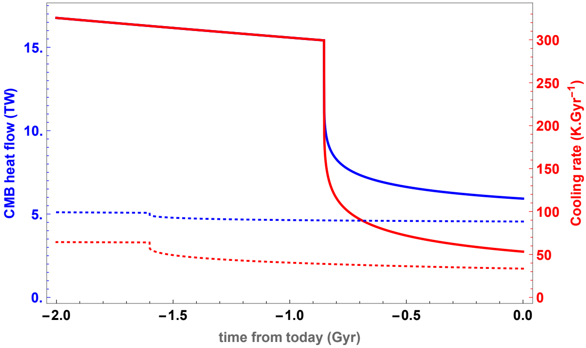
with:

$$Q_{g,Mg} = f_{g,Mg}(\alpha_c, C_m)\frac{\mathrm{d}T_{CMB}}{\mathrm{d}t}$$

$$E_{g,Mg} = \frac{Q_{g,Mg}}{T_{CMB}}$$

O'Rourke and Stevenson, 2016

CMB heat flux and rate of cooling



With Mg exsolution:

- IC age: ~ 1.6 Gyr
- Very little variation
- $E_{g,Mg} \gg E_s$

	With IC	Without IC
Larger contribution to Q_{CMB} (%) with Mg without Mg	 $Q_s \sim 50\%$ $Q_s \sim 55\%$	 $Q_s \sim 65\%$ $Q_s = 100\%$
Larger contribution to E_k (%) with Mg without Mg	 $E_{g,Mg} \sim 55\%$ $E_g \sim 50\%$	 $E_{g,Mg} \sim 80\%$ $E_s = 100\%$

Conclusion

Without Mg:

- rate of cooling at the CMB $\sim$ 300 K.Gyr^{-1}
- inner core age $\sim$ 850 Myr
- temperature at the CMB $\sim$ 4400 K (mantle melting)
- $Q_{CMB} \sim 15\,TW$

With Mg:

- rate of cooling at the CMB $\sim$ 65 K.Gyr^{-1}
- inner core age doubled
- temperature at the CMB decreased by 300 K at $t = 2$ Gyr
- $Q_{CMB} \sim 5\,TW$

And Mercury?
Mg exsolution unlikely...