Core Constraints on Deep Earth Evolution

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Img. Cred.
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What are the power sources for the dynamo over the last 3.5 Gyrs?
Generating the Geomagnetic Field

- Dynamo is powered by cooling – heat flow $Q_{cmb}$ across core-mantle boundary
- Power needed to sustain the dynamo constrains $Q_{cmb}$

Glatzmaier & Roberts (1997)

Power to sustain the dynamo constrains rate of core cooling and inner core growth.
Precipitation may occur from core formation and could significantly lower core cooling rate (O’Rourke & Stevenson (2016); Badro et al (2016, 2018); Du et al (2017, 2019)) [NB – SiO$_2$ and FeO could also precipitate (e.g. Hirose et al, 2017)]
$Q_{CMB}$ and Temperature in Time

Gubbins et al (2004); Nimmo (2015); Labrosse (2015); Davies (2015)

- Outer core
- Inner core
- $Q_{c}$
- $Q_{s}$
- $Q_{a}$
- $Q_{l}$
- $Q_{r}$
- $Q_{p}$

$Q_{cmb} = Q_{s} + Q_{L} + Q_{c} + Q_{r} + Q_{P} = A \frac{dT_{c}}{dt} + Q_{r} + Q_{p}$

- secular
- gravitational precipitation
- latent
- radiogenic

- Core cooling rate ($dT_{c}/dt$) determined from $Q_{cmb}$ (imposed by mantle convection)
$Q_{CMB}$ and Temperature in Time

Gubbins et al (2004); Nimmo (2015); Labrosse (2015); Davies (2015)

$Q_{cmb} = Q_s + Q_L + Q_c + Q_r + Q_p = A \frac{dT_c}{dt} + Q_r + Q_p$

$E_J(B) - E_a(k) = E_S + E_L + E_g + E_r + E_P = B \frac{dT_c}{dt} + E_r + E_P$
Thermal Conductivity ($k$)

Pure Fe:
De Koker et al (2012)

Mixtures:
Pozzo et al (2013);
76.8%Fe–23.2%O Gomi et al (2013, Open)
77.5%Fe–22.5%Si Gomi et al (2013, Closed)

“Low” values
Stacey & Anderson (2001)
Stacey & Loper (2007)
Konopkova et al (2016)
Xu et al (2018, hcp iron)

- ‘High’ $k$ values are 2-3 times larger than ‘low’ values
- $k$ varies significantly with depth
Model core in isolation

**Constraint:** $E_J > 0$ for last 3.5 Gyrs

**Lower(ish) bound** on cooling rate: set $E_J = 0$ before inner core formation

How do the high conductivity estimates affect models of Earth’s core evolution?

- Inner core evolution
- Core temperatures
- CMB heat flow

Omit precipitation at first..

$$Q_{cmb} = A \frac{dT_c}{dt} + Q_r + Q_P$$

$$E_J(B) + E_a(k) = B \frac{dT_c}{dt} + E_r + E_p$$
The Core Model

\[ \Delta \rho = 0.8 \pm 0.2 \text{ g/cc} \]  
(Masters & Gubbins, 2003)

The inner core boundary is indicated on the graph.
The Core Model

\[ \Delta \rho = 0.8 \pm 0.2 \text{ g/cc} \] (Masters & Gubbins, 2003)

The Core Model

\[ \Delta \rho = 0.8 \pm 0.2 \text{ g/cc} \] (Masters & Gubbins, 2003)

<table>
<thead>
<tr>
<th>( \Delta \rho ) (kg/m(^3))</th>
<th>%Fe</th>
<th>%O</th>
<th>%Si</th>
<th>( T_i )</th>
</tr>
</thead>
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<tr>
<td>0.6</td>
<td>82</td>
<td>8</td>
<td>10</td>
<td>5900</td>
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<tr>
<td>0.8</td>
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<td>13</td>
<td>8</td>
<td>5580</td>
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<tr>
<td>1.0</td>
<td>81</td>
<td>17</td>
<td>2</td>
<td>5320</td>
</tr>
</tbody>
</table>


Stacey & Anderson (2001)
Stacey & Loper (2007)
Lower mantle solidus $T$ (Andrault et al., 2011)

Davies (2015, PEPI)
\[ \Delta \rho = 0.6 \text{ gm cm}^{-1} \]
\[ \Delta \rho = 0.8 \text{ gm cm}^{-1} \]
\[ \Delta \rho = 1.0 \text{ gm cm}^{-1} \]

High \( k \), \( h = 0 \)
High \( k \), \( h = 300 \text{ppm} \)
\( k = 46 \text{ W m}^{-1} \text{ K}^{-1} \), \( h = 0 \)

Davies et al, (Nat. Geosci., 2015)
Gravitational energy released depends on $C_m$, mass precipitated per unit T drop
Add precipitation with $C_m = 0.61 \times 10^{-5} / K$ to previous models.
Assume precipitation occurs over last 3.5 Gyrs
\[ \Delta \rho = 0.6 \text{ gm cc}^{-1} \]
\[ \Delta \rho = 0.8 \text{ gm cc}^{-1} \]
\[ \Delta \rho = 1.0 \text{ gm cc}^{-1} \]

High \( k, h = 0 \)

High \( k, h = 300 \text{ppm} \)

\( k = 46 \text{ W m}^{-1} \text{ K}^{-1}, h = 0 \)

\( C_m = 6 \times 10^{-6} \text{ K}^{-1}, h = 0 \)

\( C_m = 1 \times 10^{-5} \text{ K}^{-1}, h = 0 \)
Conclusions

Maintaining a marginal dynamo prior to inner core formation with high $k$ requires

- Primordial core temperature > present estimates of lower mantle solidus
- Inner core age < 1 Gyr (300-500 Myrs without precipitation; 500-800 Myr with precipitation)

Minimum changes over 4.5 Gyrs:

- $T_{cmb}$: 600-1800 K
- $Q_{cmb}$: 2-7 TW

Minimum present-day $Q_{cmb}$~8 – 9 TW

ICB density jump and $C_m$ are main uncertainties in current models