Core thermal history and Magnesium exsolution

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1. Scope

Thermal conductivity of iron is a key parameter for the thermal history of the Earth's core and it controls the amount of heat that is available to drive core convection. Recent high pressure experiments and ab initio calculations have found that the **thermal conductivity** of iron is likely **two to three times larger** than previously thought, decreasing significantly the amount of power available to generate the magnetic field in the core.

The dynamo in the core is mainly powered by the energy released due to inner core solidification. The heat arising from radiogenic elements in the core could also be an important contribution. To maintain the same magnetic field with the new value of thermal conductivity, the core cooling rate would increase, **melting the base of the initial mantle** and leading to a **younger inner core**. Increasing the thermal conductivity may also give rise to a **stable stratification at the top of the core**. This has significant consequences on the convection in the outer core and therefore on the dynamo process: stratification prevents radial motion at the CMB and a younger inner core means that thermal convection, less efficient than the chemical convection initiated by the inner core solidification, must drive the dynamo for longer. We therefore need an additional source to power the dynamo.

2. MgO exsolution

As a result of giant impacts during Earth's accretion, such as the Moon-forming impact, and from the resulting extreme high temperatures, large amount of magnesium could have been dissolved in the core forming metal (Badro et al. 2016). The amount of magnesium that can be dissolved in liquid iron decreases with temperature, therefore subsequent cooling saturates the core with Mg and induces MgO exsolution. The buoyancy flux produced by the Mg depleted fluid at the top of the core generates a substantial amount of gravitational energy and thus is a likely important energy source for the dynamo.

3. Model

Thermal evolution of the core and the mantle deduced from global energy and entropy balance

A. Core

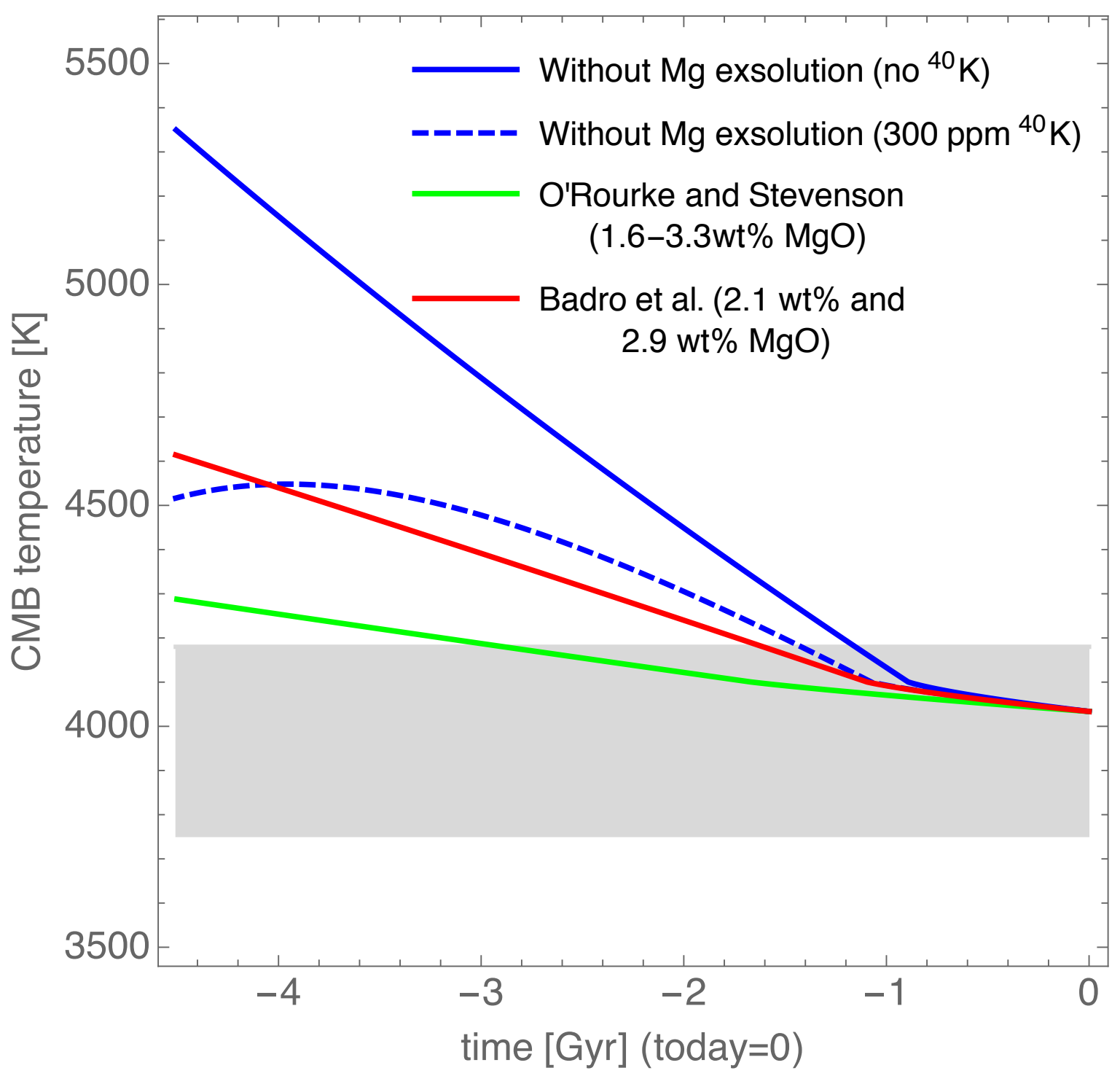
- Based on Gubbins (2003, 2004) and Davies (2015)
- ICB density jumb: $\Delta\rho = 0.8$ g.cm^{-3} (Masters and Gubbins, 2003)
- Marginal dynamo (entropy sets to zero) for all time: minimal power needed to generate a dynamo
- Radioactive heating: 0 or 300 ppm ^{40}K

- Mg exsolution: temperature independent (O'Rourke and Stevenson, 2016) or temperature dependent (Badro et al., 2016)
- Two initial MgO abundances from Badro et al. (2016): 2.1 wt% (impactor mass: 2.5% of Earth's mass) and 2.9 wt% (impactor mass: 10% of Earth's mass). The initial abundance in O'Rourke and Stevenson (2016) is between 1.6-3.3 wt%.
- Full mixing of the impactor with the Earth's core, forming an homogeneous core (Badro et al. 2016)

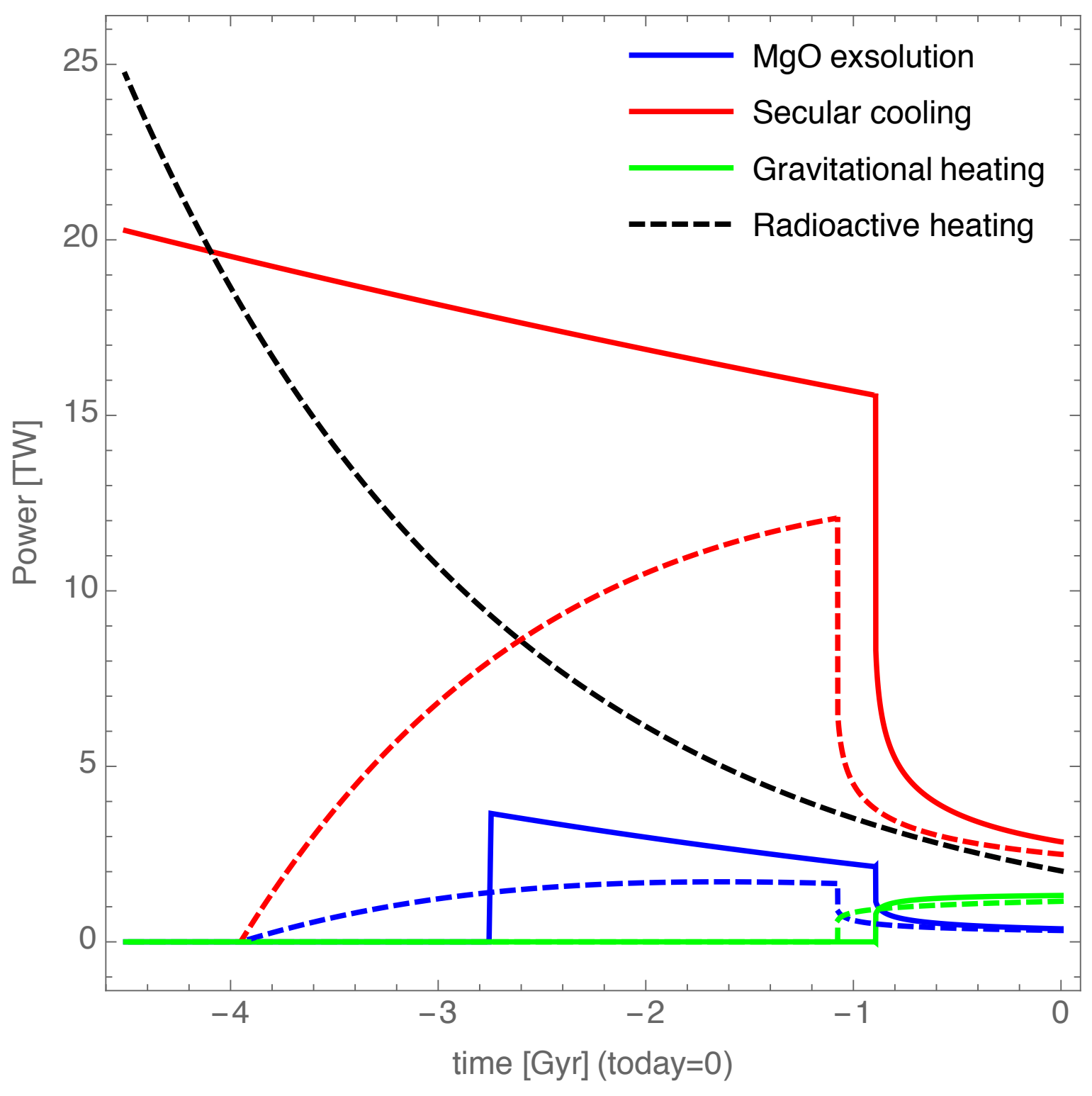
B. Global model

- Based on Driscoll and Bercovici (2014)
- Radioactive heating: ∼300 ppm ^{40}K in the core; concentrations of uranium, thorium and potassium in the mantle such that the radioactive heating is 13 TW today
- Heat sources in the mantle are CMB heat flow from the core and radioactive heating. The mantle cools by heat conducted through the upper boundary layer to the surface, and by upwelling molten rock solidifying at the surface (Driscoll and Barnes, 2015).

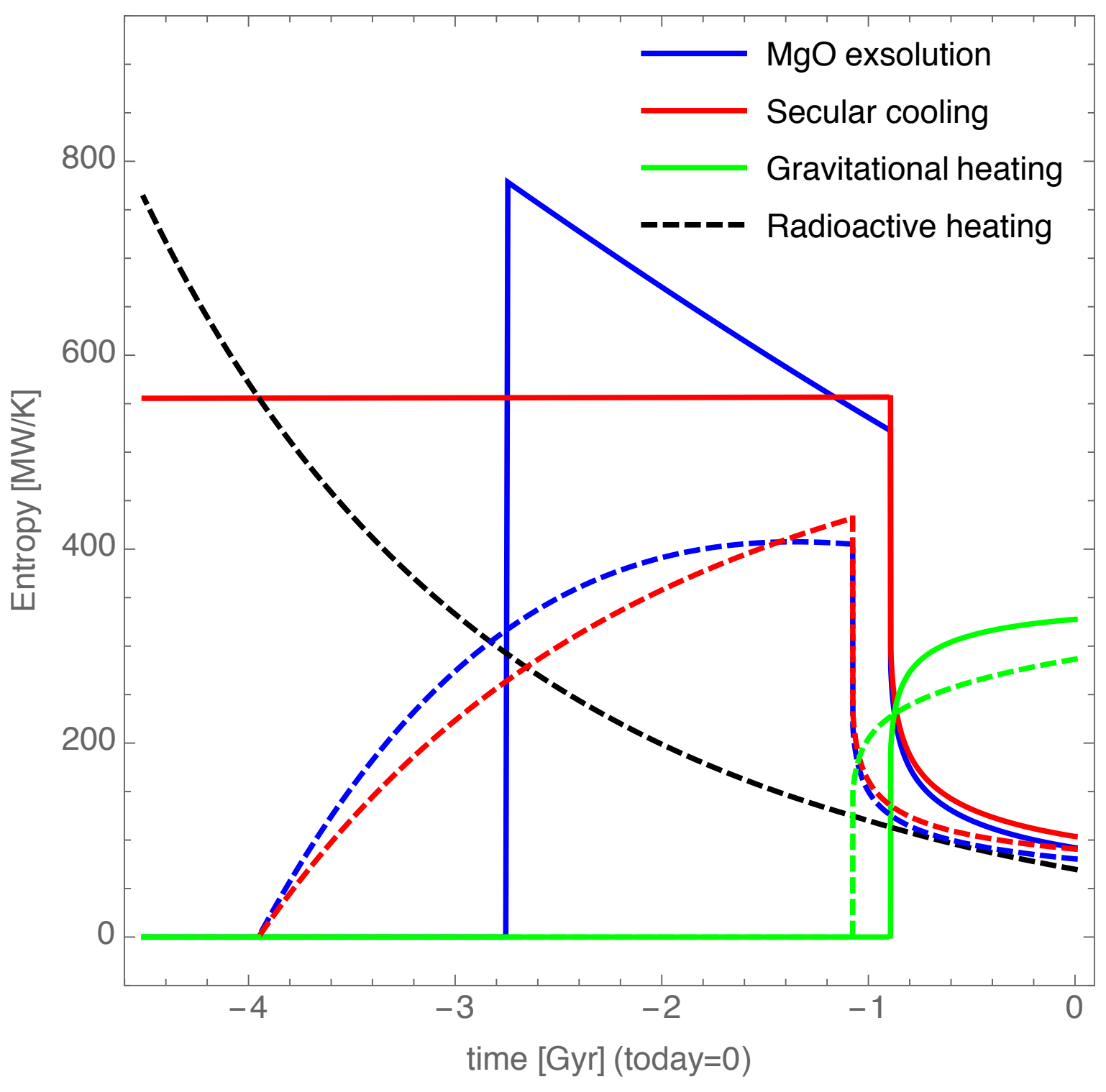
4. Core thermal evolution



Core-mantle boundary temperature for marginal dynamo with and without radioactive heating and with MgO exsolution according to Badro et al. and to O'Rourke and Stevenson. Models with MgO do not include radioactive heating. The light gray zone represents the lower mantle solidus: from 3570 K for wet-pyrolite to 4180 K for dry-peridotite (Andrault et al. 2016).



Principal core power contribution components and contribution of MgO exsolution (Badro et al., initial MgO abundance of 2.1 wt%) to the energy balance, assuming the core-mantle boundary temperature profile and the cooling rate from the models without exsolution. The dashed lines represents energy contributions from model with 300 ppm ^{40}K, the solid lines are for model with no radioactive heating. Latent heat contribution is very similar to gravitational release. CMB heat flux is about 15-20 TW before inner core formation and about 5-6 TW (no ^{40}K) or 7-10 TW (300 ppm ^{40}K) before inner core formation.

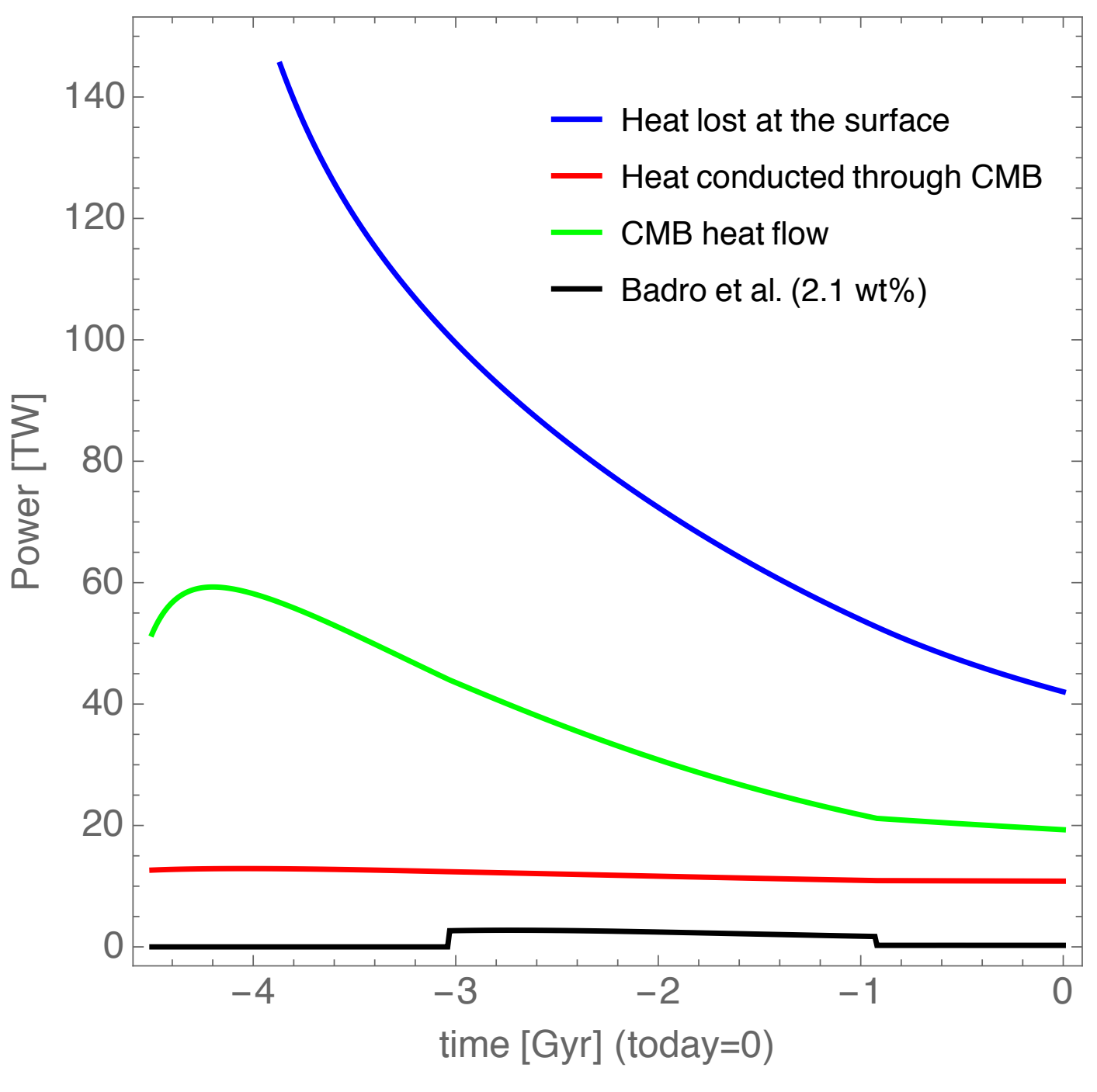


Principal entropy contributions and exsolution entropy contribution from the exsolution energy presented on the left (Badro et al., 2.1 wt% MgO). Dashed lines represents entropy contributions from model with 300 ppm ^{40}K, and solid lines are for model with no radioactive heating. Latent heat contribution is very similar to gravitational entropy, and entropy of thermal conduction is about 550 MW/K during all the evolution.

- Lower mantle melted during at least half the thermal history for all models. The decreasing effect of MgO exsolution on the CMB temperature is similar than ^{40}K radioactive heating.
- Badro et al.:
  - initial MgO abundance only affects the onset of exsolution
  - 0 ppm ^{40}K and 2.1 wt% MgO (figure): before 1.7 Gyr, below saturation for the temperature profile used ⇒ no exsolution
  - 0 ppm ^{40}K and 2.9 wt% MgO: exsolution begins 1 Gyr sooner than for initial abundance of 2.1 wt% ⇒ higher cooling rate ⇒ higher power and entropy generated at the beginning (about 5 TW and 900 MW/K)
  - 300 ppm ^{40}K: same behaviour for both the abundances considered: CMB temperature is low enough for exsolution to start at the beginning of evolution.

  - Energy (0 and 300 ppm ^{40}K): small contribution during all the evolution for both initial abundances
  - Entropy (0 ppm ^{40}K): largest contribution when present before inner core formation; during innner core formation, lower than gravitational contribution and similar to secular cooling
  - Entropy (300 ppm ^{40}K): contribution similar to secular cooling; important contribution from radioactive heating in the early times;
- O'Rourke and Stevenson:
  - Energy: larger contribution than exsolution from Badro et al.: from 10 TW to 8 TW (less than 7 TW for 300 ppm ^{40}K) before inner core formation
  - Entropy (0 and 300 ppm ^{40}K): largest contribution before inner core formation (2000 MW/K - about 1500 MW/K with and without radioactive heating), and larger contribution than gravitational entropy during inner core formation
- MgO exsolution generates heat in the core, decreasing its cooling rate and therefore the CMB heat flow. For marginal dynamo: 9 TW before inner core formation and about 5 TW during inner core formation (Badro et al.); about 5 TW during all the evolution for O'Rourke and Stevenson. It is below the heat conducted through the CMB along the adiabat, leading to thermal stratification in the core, unlike the models with not exsolution before inner core formation. To avoid stratification, the CMB heat flow should be larger today than about 14.6 TW for all models. Estimates ranges between 6 and 15 TW (Nimmo et al. 2007, Driscoll and Bercovici 2014, Pozzo et al. 2014).

5. Global model: preliminary result



Principal power contributions from mantle and core: heat lost at the surface from molten rock and conduction, heat conducted and heat flow through the CMB, and MgO exsolution contribution. Initial MgO abundance of 2.1 wt% (Badro et al.).

- Energy: MgO exsolution: smallest contribution to energy balance
- Entropy: MgO exsolution: large entropy term, similar to values from the core model
- CMB temperature profile: varying from about 4900 K in the early time to 4100 K today
- CMB heat flow much larger than energy from thermal conduction through CMB

6. Conclusion

- CMB temperature is decreased with MgO exsolution but the lower mantle is still molten during a large part of the evolution (core and global models)
- When present, MgO exsolution entropy contribution is the largest one ⇒ can power the dynamo before inner core formation
- Power generated by MgO exsolution is decreased because of reduced cooling rate due to radioactive heating
- MgO exsolution decrease the CMB heat flow by heating the core. For marginal dynamo, it leads to thermal stratification in the core, unlike the model with no exsolution. To avoid stratification, the CMB heat flow should be larger today than about 14.6 TW.

Note According to new calculations and experiments (Pourovskii et al. 2016, Konôpková et al. 2016), the thermal conductivity of iron could be lower than its new value. Influence of MgO exsolution will be studied further in this case in a future work.

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